16. Power Generation

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The chapter contains 32 sections. Section 16.1 gives an introduction to the principle of energy supply. This section also provides the state of the art of the economics of various energy resources. Different types of fuels and their characteristics are discussed in Sect. 16.3. The conversion of different forms of energy has been explained in Sect. 16.5. Working principles of different power plants like gas turbines, the internal combustion (IC) engine, fuel cells, nuclear, and combined cycle system are discussed in Sects. 16.6–16.10.

Section 16.11 explores the inherent features of the integrated gasification combined cycle system. Various types of gasifiers and their working procedures are explained in this section. Section 16.12 provides updated information about magnetohydrodynamic power generation and detailed information about various types of cogeneration system is also explained in Sect. 16.13.

Sections 16.14 and 16.15 explain the transformation of regenerative energies. These sections are mainly devoted to wind and solar energy conversion. Harvesting solar energy using solar ponds and solar chimneys is also explained in this section. The concept and working principle of the heat pump is explained in Sect. 16.16.

Section 16.17 contains the information about energy storage and distribution systems. Energy storage is used to offset the adverse effects of fluctuating demands for electricity and to assure a steady output from existing power plants. Various energy storage devices like pumped hydro, thermal energy, and hydrogen energy are described.

The furnace is the heart of a power generation system. Understanding its internal features and working principle is very important for a power plant professional. Section 16.18 satisfies these needs. It not only provides the characteristics of furnace combustion, but also provides the emission characteristics of furnace. Recent combustion technologies like fluidized bed combustion, bubbling fluidized bed combustion, and circulating fluidized bed combustion are also explored in Sect. 16.19.

Section 16.21 provides more details about the working principles of various types of burners. Inside the furnace the fuel must be evenly dispersed in the combustion airstream such that the fuel and air can come into intimate contact. Failure to achieve this results in unburnt or partially burnt fuel. The burner design attempts to achieve this by using a variety of techniques. Sections 16.22 and 16.23 facilitate understanding of various furnace accessories and technologies available to control emission.

The boiler is a key component in modern, coal-fired power plants; its concept, design, type, and integration into the overall plant considerably influence costs. The operating behavior and availability of the power plant are discussed in Sect. 16.24. Details of the various components of a steam generator are provided in Sect. 16.25.

Energy balance analysis and the efficiency calculation of furnace are described in Sects. 16.26–16.28. Thermodynamic calculations such as furnace design, boiler strength calculations, and heat transfer calculations are discussed in Sects. 16.29 and 16.30. Various types of nuclear reactors and their working principles are elaborated in Sect. 16.31. Finally, Sect. 16.32 is devoted to a discussion of future prospects and conclusions.

16.1 Principles of Energy Supply

Energy exists in many forms such as thermal energy, chemical energy, mechanical energy, potential energy, kinetic energy, and nuclear energy. Electrical energy is a desirable form of energy, because it can be generated centrally in bulk and transmitted economically over long distances. The requirement for energy is the demand for so many tonnes of coal, barrels of oil, cubic meters of gas, and so on. With the ever-increasing per-capita energy consumption and exponential growth in population, technologists already foresee the end of the Earth's non-replenishable fuel resources.

16.1.1 Planning and Investments

Investment planning for power plants requires a long-term plan, which covers facility investment such as the construction of new power plants or the replacement of existing plants with a newer one in an uncertain environments. Capital investment is a prerequisite for energy development as it is highly capital intensive. Investments in energy plants, equipment, and infrastructure (transportation, availability of fuel, water, communications, environment compatibility etc.) must be viewed

in the framework of economic growth, savings, and the size and degree of liberalization of capital markets.

According to the International Energy Agency (IEA), investment in electricity generation capacity will be about \$4.6 trillion and installed capacity will rise from 3498 GW in 2000 to 7157 GW by 2030. As around 1000 GW of capacity is likely to be retired over this period, a total of 4700 GW of new build is required, costing around \$4.28 trillion.

16.1.2 Economics of Gas

The yearly world demand for natural gas was 95.50 trillion cubic feet in 2003 and is rising gradually. In the year 2001 the consumption of natural gas was only 89.31 trillion cubic feet. Figure 16.1 provides information about the shares of electricity generation by fuel. Electricity generation from gas increased from 12.1% in 1973 to 19.4% in 2003.

Natural gas has the advantage over most other energy resources because of its great operational flexibility and the ease with which incremental gas supplies can be moved to generators. Various studies have revealed that gas is a preferred energy source for new generating capacity.

According to the statistics of the International Energy Agency, worldwide electricity production using gas in the year 2003 was 3 224 699 GW h out of a total electricity production of 16 741 884 GW h. According to the results of an IEA survey natural gas is tending to gain and coal to lose market share as the industry moves from a regulated position to a competitive environment.

Gas-fueled power plants have low capital cost. In 2003, 16% of the world's electricity was generated by natural gas. Technology transfer from developed countries will be required to meet this need. Pipeline transmission of gaseous fuel is capital intensive and allows less flexibility in the choice of buyers and sellers.

16.1.3 Economics of Electricity

A power plant should provide a reliable supply of electricity at minimum cost and minimum pollution to the consumer. The total price we pay for energy from power plants consists of:

1. Capital cost
2. Operating costs

Capital cost depends entirely on plant investment and includes:

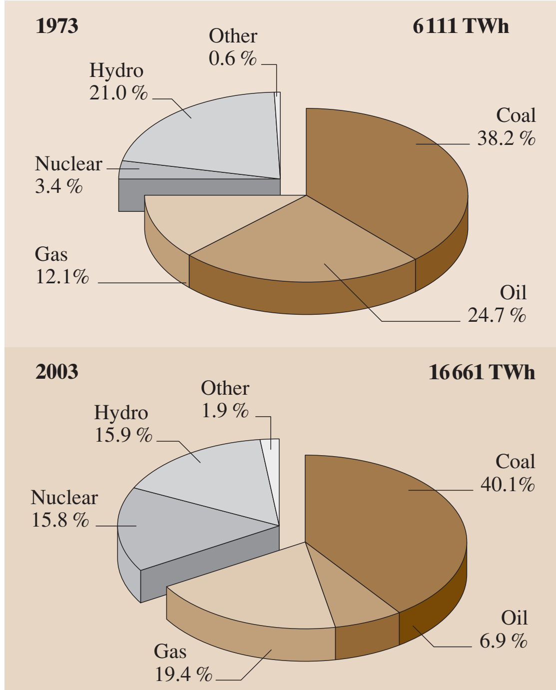

Fig. 16.1 Total energy shares of primary energy for electricity 2003 (Source: energy statistics from the IEA)

1. Interest
2. Depreciation
3. Taxes
4. Insurance

Operating cost includes the cost of operation, maintenance, and fuel.

Operating costs are inversely proportional to the capacity factor. Operating and maintenance costs mainly depend on the type of unit and the fuel used. Maintenance costs may be reduced if the unit is not operating or is operated at low load.

With the increase in economic growth, the consumption of electricity also increases. Electricity demand in India has been increasing rapidly, and the 534 billion kWh produced in 2002 was almost double the 1990 output, although it represents only 505 kWh per capita for the year. The amount and cost of electricity depends upon the fuel used.

16.1.4 Economics of Remote Heating

The cost of generating useful heat should be identified with the value of the *lost* electricity. The total

cost of waste heat has two components: the production cost at the plant and the distribution cost. The distribution component is calculated from the capital charges and maintenance expense for the pipeline system conveying warm water or steam from the plant to customers.

District heating is already widely used in central core areas of large cities. Many large buildings can be heated by steam or hot water from a single large central combustion plant. Also, space cooling can be provided by using the hot water or steam to actuate an absorption-type refrigeration plant.

16.2 Primary Energies

Primary energy is contained in raw fuels and any other forms of energy received by a system as input to the system. Primary energy is transformed in energy conversion processes to more convenient forms of energy and cleaner fuels. The most important primary energy sources are the carbon-based fossil energy sources. Fossil fuels (oil, coal, and natural gas) are called nonrenewable energies, and come from the long-term decomposition of plant and animal matter over millions of years. Sun is the main source of energy from which all of the above energy resources are derived.

16.3 Fuels

Fuels are chemical substances which may be burned in oxygen to generate heat. They mainly consist of carbon and hydrogen and sometimes a small amount of sulfur or minerals, and may be solid, liquid, or gaseous. Coal and coke are examples of solid fuels. Petroleum oils are usually a mixture of several liquid fuels. Gaseous fuels may be a mixture of gases such as methane (CH_4), ethane (C_2H_6) and so on.

16.3.1 Solid Fuels

Solid fuel is a term given to various types of solid materials that provide energy. This energy is usually released by combustion. Coal and coke are examples of solid fuels.

16.3.2 Liquid Fuels

Most liquid fuels are derived from fossil fuels. These can be classified according to their volatility (the ease with which they evaporate and turn into vapor). The most volatile fuels are gasoline and kerosene. Less volatile fuels are used in diesel engines and residual fuels, of varying viscosities, are often used in boilers. Ethanol produced from the fermentation of sugar is a prominent liquid fuel.

16.3.3 Gaseous Fuels

Gas is a preferred fuel, the combustion of which offers more environmental friendliness over the other fossil fuels. It burns more readily and completely than other fuels. Gaseous fuels are the most convenient, requiring the least amount of handling, and are the most maintenance free. Gas is odorless and colorless. Because gaseous fuels are in a molecular form, they are easily mixed with the air as required for combustion, and are oxidized in less time than is required to burn other types of fuel. A mixture of methane (CH_4) and ethane (C_2H_6) is an example of a gaseous fuel.

16.3.4 Nuclear Fuels

Fuels such as uranium or thorium that can be used in nuclear reactors as a source of electricity are called nuclear fuels. The energy derived during fission or fusion processes is called nuclear energy. Examples of nuclear fuels are: ^{235}U, ^{238}U, and ^{239}Pu.

16.3.5 Regenerative Energies

Regenerative or renewable energies are those energy sources or energy carriers that naturally renew themselves within human timescales. Regenerative energies

are available everywhere. Effective utilization of these resources is a very challenging task [16.1]. The renewable sources of energy include hydropower, solar, wind, and biomass [16.2].

16.4 Transformation of Primary Energy into Useful Energy

Energy has become an essential driving force of the economy. In fact, it assumes numerous forms: chemical energy in fossil fuels or the biomass, kinetic energy in waterfalls or the wind, electromagnetic energy from the sun, nuclear energy in uranium, as well as the electrical or thermal energy that is put to numerous uses. The sun is the major source of energy from which all energy resources are derived. Figure 16.2 shows the various forms of energy derived from the sun. It represents all the fossil fuels (oil, gas, and coal) derived from the sun by various means of transformation such as vegetation, chemical energy conversion, and finally fossilization.

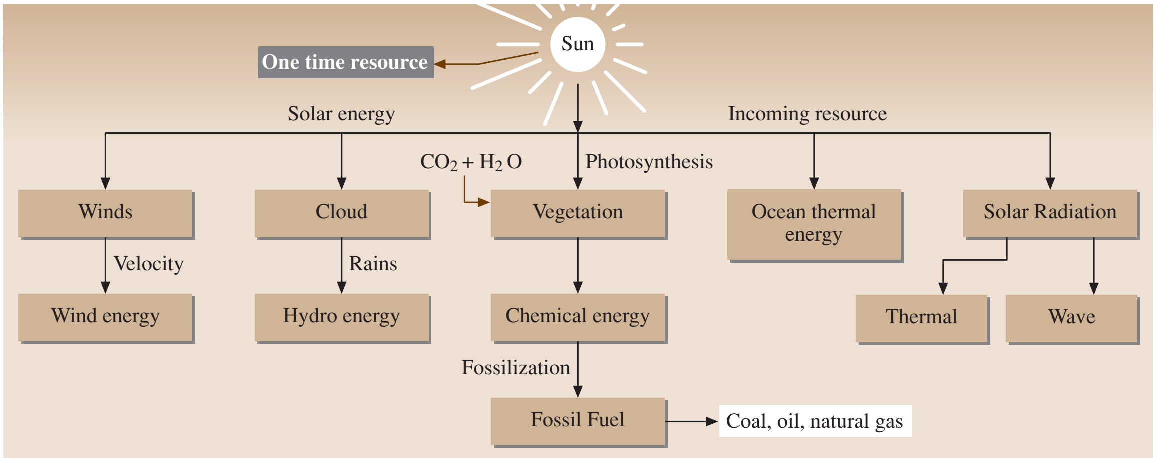

Fig. 16.2 Energy system diagram

16.5 Various Energy Systems and Their Conversion

Conversion of one form of energy into another form of energy is essential in order to utilize the maximum potential of energy resources. Efficient generation of electricity from various energy resources is one of the challenging tasks for the scientist. Efficient utilization of various sources of energy leads to a strong economy and promotes the wealth of the nation. Figures 16.3–16.5 depict various energy systems and their conversion process.

The sun heats our atmosphere unevenly, so some patches become warmer than others. These warm patches of air rise and other air blows in to replace them – and we feel a wind blowing. We can use the energy in the wind by building a tall tower, with a large propeller on the top.

The current global average conversion efficiency for coal-fired electricity generation is 34% and that for gas-fired electricity generation 37%. Modern coal-fired power plants are operating at a higher efficiency of 43–48 %.

16.5.1 Generation of Electrical Energy

Electric energy is the flow of electric power or charge. It is a secondary energy source, which means that we get it from the conversion of other sources of energy, such as coal, natural gas, oil, nuclear power, and other natural sources, which are called primary sources. The energy sources we use to make electricity can be renewable or nonrenewable, but electricity itself is either renew-

able or nonrenewable. Electricity generation from the combustion of fuel is reported under combustion-based power station.

16.5.2 Steam Power Cycle

The Rankine cycle is a thermodynamic cycle and is used in a variety of power plants. The simplest arrangement of the steam power plant is that without regeneration and reheat, as shown in Fig. 16.7. A simple Rankine cycle consists of four main components (steam generator, turbine, condenser, and pump). Additional components are sometimes added to enhance cycle performance and to improve efficiency. This cycle is named after William John Macquorn Rankine (1820–1872), who established it as the fundamental cycle for a steam power plant. In a simple steam power plant, which works on a Rankine cycle, heat is added reversibly at a constant pressure. The efficiency of the Rankine cycle is a function of the temperature of heat rejection and the mean temperature of heat addition. The higher the mean temperature of heat ad-

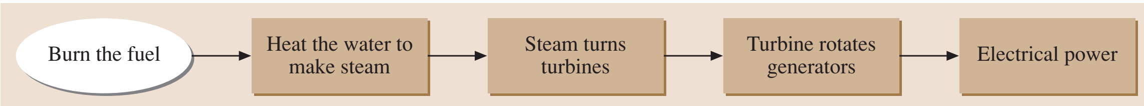

Fig. 16.3 Structure of energy systems – fossil sources

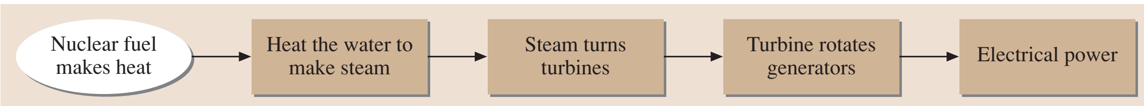

Fig. 16.4 Structure of energy system – nuclear fuels

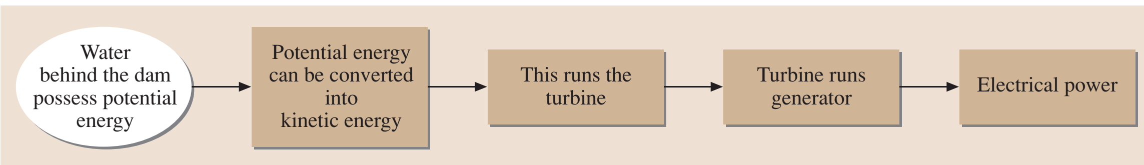

Fig. 16.5 Structure of energy systems – hydro fuels

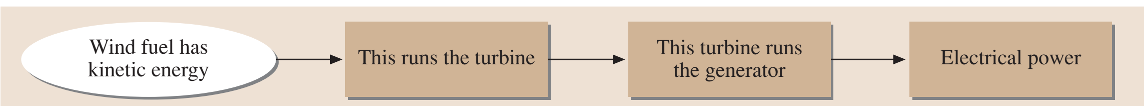

Fig. 16.6 Structure of energy systems – wind fuels

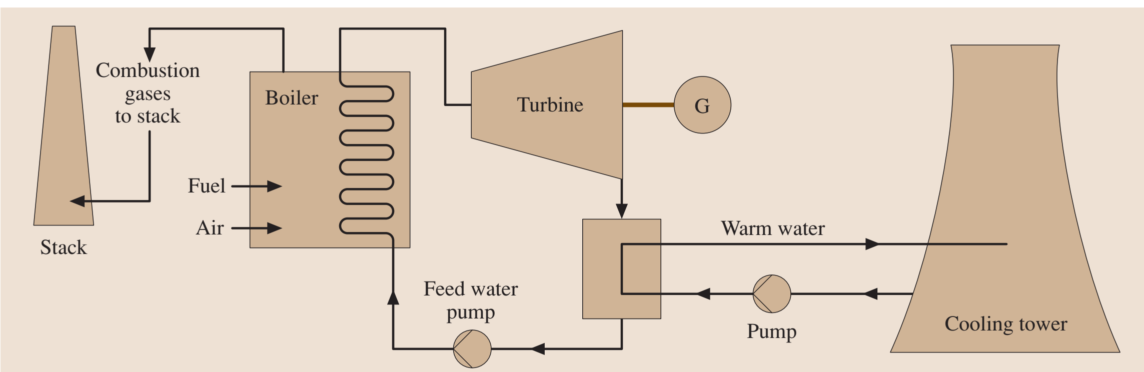

Fig. 16.7 Layout of a simple Rankine cycle power plant

dition the higher the efficiency. The working fluid in a Rankine cycle follows a closed loop and is reused constantly.

16.5.3 Process of the Rankine Cycle

There are four processes in the Rankine cycle, each changing the state of the working fluid. These states are identified in the T–S (temperature–entropy) diagram shown in Fig. 16.8.

Process 1–2. First the working fluid is pumped (isentropically) from low to high pressure by a pump. Pumping requires a power input (for example, mechanical or electrical).

Process 2–3. The high-pressure liquid enters a boiler, where it is heated at a constant pressure by an external heat source to become a superheated vapor. The common heat sources for power plant systems are coal, natural gas, and nuclear power.

Process 3–4. The superheated vapor expands through a turbine to generate power output; ideally this expansion is isentropic. This decreases the temperature and pressure of the vapor.

Process 4–1. The vapor then enters a condenser, where it is cooled to become a saturated liquid. This liquid then reenters the pump and the cycle repeats.

In order to improve coal-fired power plant efficiency, leading to a proportional reduction in coal consumption and carbon dioxide emissions, it is widely accepted that the domestic power industry must move from subcritical to supercritical steam cycles.

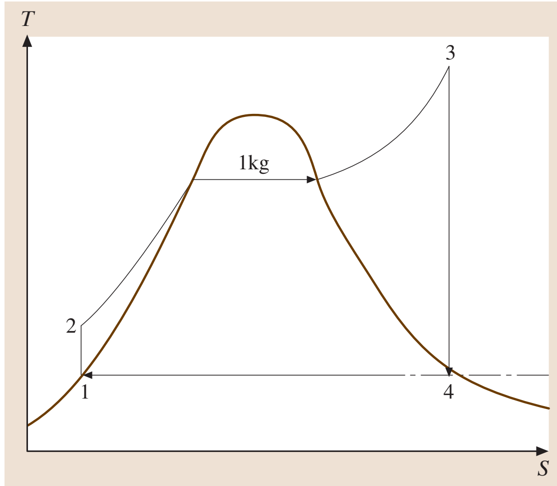

Fig. 16.8 T–S diagram of a simple Rankine cycle

Reaching 45% efficiency is possible with the help of a supercritical (SC) Rankine steam cycle employing a reheat and regeneration mode and operating at 250 bar and 540 °C. Today, ultra-supercritical steam (USC) parameters of 300 bars and 600/600 °C can be realized, resulting in 42% (HHV – higher heating value) efficiency for bituminous-coal-fired power plants [16.3].

The improved efficiency represents reductions of about 15% in all emissions including CO_2, compared to those from installed capacity. The challenges of coal-based power generation are environmental; the future technologies are near-zero emission and high-efficiency plants equipped to reduce CO_2 emission.

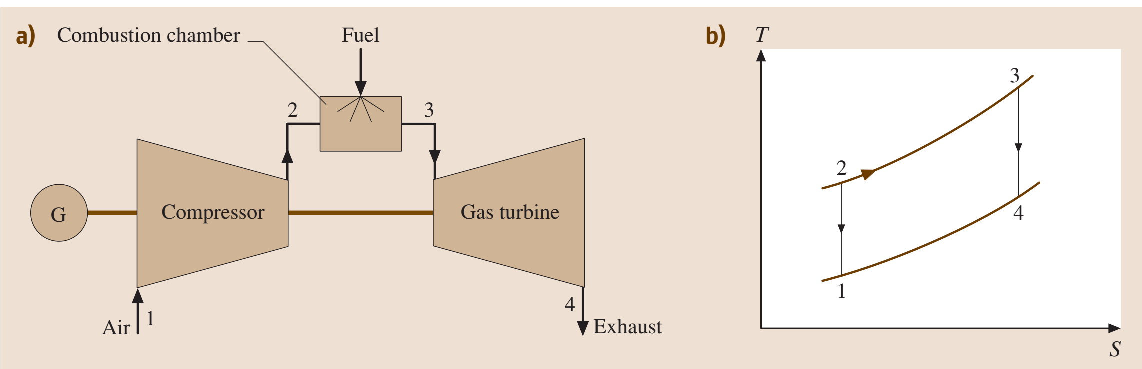

Fig. 16.9 Arrangement of an open-cycle gas turbine plant

16.6 Direct Combustion System

The economics of power generation by gas turbines is now quite attractive due to their low capital cost and high reliability and flexibility in operation. Another outstanding feature is their capability to start quickly and to use a wide variety of fuels from natural gas to residual oil or powdered coal.

16.6.1 Open-Cycle Gas Turbine Power Plant

The essential components of a gas turbine power plant are the compressor, combustion chamber, and the turbine. The air standard cycle of gas turbine power plant is the Brayton cycle shown in Fig. 16.9. It consists of two reversible adiabatic processes and two constant-pressure processes. Gas turbine plants can be operated either in an open or closed system configuration.

Analysis

1–2: Work input

$$w_{\text{comp}} = h_2 - h_1 = c_p(T_2 - T_1)\,, \tag{16.1}$$

2–3: Heat input

$$q_{\text{in}} = h_3 - h_2 = c_p(T_3 - T_2)\,, \tag{16.2}$$

3–4: Work output

$$w_{\text{tur}} = h_3 - h_4 = c_p(T_3 - T_4)\,, \tag{16.3}$$

4–1: Heat rejection

$$q_{\text{out}} = h_4 - h_1 = c_p(T_4 - T_1)\,. \tag{16.4}$$

Isentropic processes

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}\,, \tag{16.5}$$

$$\frac{p_3}{p_4} = \left(\frac{v_4}{v_3}\right)^{\gamma} = \left(\frac{T_3}{T_4}\right)^{\frac{\gamma}{\gamma-1}}\,. \tag{16.6}$$

Constant-pressure processes

$$p_3 = p_2 \quad \text{and} \quad p_4 = p_1\,; \tag{16.7}$$

$$\begin{aligned} r_p &= \frac{p_2}{p_1} = \frac{p_3}{p_4} = \left(\frac{v_1}{v_2}\right)^{\gamma} = \left(\frac{v_4}{v_3}\right)^{\gamma} \\ &= \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{T_3}{T_4}\right)^{\frac{\gamma}{\gamma-1}}\,, \end{aligned} \tag{16.8}$$

where r_p is the pressure ratio

$$T_2 = T_1(r_p)^{\frac{\gamma-1}{\gamma}} = T_1\rho\,, \tag{16.9}$$

and

$$\rho = (r_p)^{\frac{\gamma-1}{\gamma}}\,, \tag{16.10}$$

$$T_4 = \frac{T_3}{(r_p)^{\frac{\gamma-1}{\gamma}}} = \frac{T_3}{\rho}\,, \tag{16.11}$$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{c_p\left(\frac{T_3}{\rho} - T_1\right)}{c_p\,(T_3 - \rho T_1)} = \frac{1}{r_p^{\frac{\gamma}{\gamma-1}}}\,, \tag{16.12}$$

$$w_{\text{net}} = c_p\left[T_3\left(\frac{\rho-1}{\rho}\right) - T_1(\rho-1)\right]\,, \tag{16.13}$$

$$\begin{aligned} &= c_p(\rho-1)\left(\frac{T_3}{\rho} - T_1\right) \\ &= c_p\left(\frac{\rho-1}{\rho}\right)(T_3 - \rho T_1)\,. \end{aligned} \tag{16.14}$$

The thermal efficiency can also be written as

$$\eta_{\text{th}} = \frac{1}{\rho} = \frac{1}{r_p^{\frac{\gamma}{\gamma-1}}}\,. \tag{16.15}$$

It may be noted that in a simple gas turbine cycle the cycle efficiency is a function of the pressure ratio only. The gas turbine inlet temperature is an important parameter of efficiency. The present state of the art temperature is 1570 K, but research on closed-cycle steam cooling of turbine blades, protective surface coating of combustor liners, and new ceramic structural parts of the turbine are areas of research that will lead to higher gas turbine inlet temperatures.

Merits and Demerits of the Brayton Cycle

1. Very compact, which is why it is used in aircraft.
2. It demands extremely high quality and costlier fuel.
3. The pressure of the exit gases should always be just above atmospheric pressure.
4. The compressor requires a large power input. In consumes more power than is produced from the steam turbine.
5. It has a lower cycle efficiency, due to the large exhaust loss.

16.7 Internal Combustion Engines

The internal combustion (IC) engine is one of the greatest inventions today. Internal combustion engines can be run by p.t.o., diesel, gasoline, methane, or natural gas. Internal combustion engines for power production are generally fueled by diesel.

Reciprocating engines have usually been employed for distributed power generation for the past few decades. Power generation from a diesel engine generator is the most cost-competitive technology to provide power to a small number of consumers. It is appropriate for an electrical load of about 0.01–50 MW.

Internal combustion engines have one or more cylinders in which the combustion of fuel takes place. The engine, which is connected to the shaft of the generator, provides the mechanical energy to drive the generator to produce electricity. The following are the benefits of IC engines for power production:

1. Easy to transport and install.
2. Like gas turbines, they are usually operated during periods of high demand for electricity.

16.8 Fuel Cells

A fuel cell is an electrochemical device that converts the chemical energy of the fuel directly into electrical energy. It consists of an electrolyte layer in contact with a porous anode and cathode on the sides. In a typical fuel cell gaseous fuels are fed continuously to the negative electrode and an oxidant is fed continuously to the positive electrode.

Electrochemical reactions take place at the electrodes to produce an electric current. In general, the oxidation of H_2, CO, CH_4, and higher hydrocarbons in fuel cells that produces power also produces rejected heat. This heat arises from two sources: when the entropy decreases, ΔS resulting from the overall oxidation reaction, accompanying the usual decrease in the number of moles of gases from reactants to products and due to the irreversible process occurring in the operation of the cell. Heat from these two sources must be rejected from the fuel cell in order to maintain the temperature at a desired level. In the case of hybridization, the efficiency is the ratio of the sum of stack electricity and the power generated by the bottoming cycle to the lower calorific value of the fuel consumed. This can be accomplished by three cycles, namely the regenerative Brayton cycle, the combined Brayton–Rankine cycle, and the steam-turbine-operated Rankine cycle.

The regenerative Brayton cycle in Fig. 16.10 shows a gas turbine compressor for the air flow to the cell. The flow then passes through a countercurrent recuperative heat exchanger to recover heat from the combustion product gases leaving the gas turbine. The air and the fuel streams then pass into the cathode and anode compartments of the fuel cell(s). The air and fuel streams

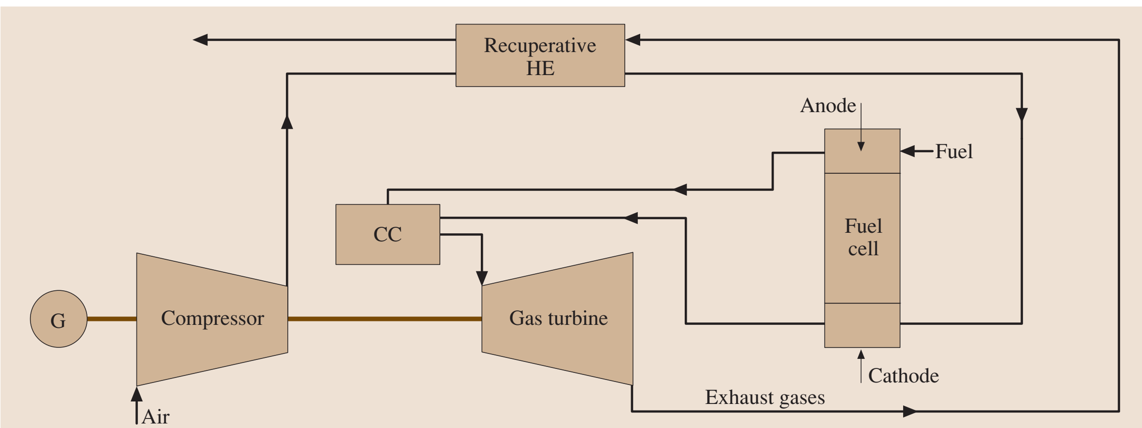

Fig. 16.10 Regenerative Brayton-cycle fuel-cell power system. (CC – combustion exchanger, HE – heat exchanger)

leaving the cell(s) enter the combustor, where they mix and the residual fuel burns. The combustion products enter the turbine, expand, and generate additional power. The turbine exhaust gases pass through the recuperative exchanger to the stack.

The overall solid oxide fuel cell reactions are

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O\,, \quad \Delta H_{298} = -241\,\mathrm{kJ/mol}\,, \tag{16.16}$$

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2\,, \quad \Delta H_{298} = -283\,\mathrm{kJ/mol}\,. \tag{16.17}$$

The ideal or equilibrium potential (E) for the above overall reactions can be calculated by the Nernst equation

$$E = E^0 + \frac{RT}{2F}\ln\left(\frac{P_{H_2}P_{O_2}^{1/2}}{P_{H_2O}}\right) \quad \text{and}$$

$$E = E^0 + \frac{RT}{2F}\ln\left(\frac{P_{CO}P_{O_2}^{1/2}}{P_{CO_2}}\right)\,. \tag{16.18}$$

Fuel cell power output

$$= \text{voltage (cell potential)} \times \text{current (load)}\,. \tag{16.19}$$

The total power and total efficiencies of the hybrid cycle are calculated as

$$P_{SOFC} = N_{cell}P_{cell}\eta_{DC/AC}\,, \tag{16.20}$$

$$P_{GT} = (P_{EXP} - P_{COMP})\eta_{GEN}\,, \tag{16.21}$$

$$P_{TOTAL} = P_{SOFC} + P_{GT} - P_{AUX}\,, \tag{16.22}$$

$$\eta_{ele} = \frac{P_{TOTAL}}{\sum N_c LHV_c}\,, \tag{16.23}$$

where P_{SOFC} is the electrical power output from the fuel cell, P_{GT} is the power output from the gas turbine, P_{aux} is the power consumed by the auxiliary units, LHV_c is the lower heating value, and N_c is the number of cells.

The Siemens Westinghouse Power Corporation of Pittsburgh developed and fabricated the first advanced power plant to combine a solid oxide fuel cell and a gas turbine. The microturbine generator was manufactured by Northern Research and Engineering Corporation of Woburn. The factory acceptance test was completed in April 2000. Southern California Edison is operating the new hybrid plant at the National Fuel Cell Research Center at the University of California, Irvine. A year of testing in a commercial setting will be performed at this site. The system cycle is expected to generate electric power at 55% efficiency. The pressurized system will generate 220 kW of power and be operated at a pressure of 3 atm. The fuel cell is made up of 1152 individual tubular ceramic cells and generates about 200 kW of electricity. The microturbine generator will produce an additional 20 kW of electricity at full power. No sulfur dioxide pollutants will be released into the air. Nitrogen oxide emissions are likely to be less than 1 ppm. A 320 kW hybrid system is also in the planning stage. An initial commercial offering of a 1 MW fuel-cell microturbine power plant in late 2002 were the end results of this Department of Energy/Siemens Westinghouse partnership program. Global electricity generating capacity from fuel cells will grow from just 75 MW in 2001 to 15 000 MW by 2010. The cost of generating electricity (> \$2000/kW) is very high for fuel cell, which restricts its wideusage.

16.9 Nuclear Power Stations

Due to the depleting nature of coal reserves, switching from coal to nuclear is mandatory today. In fact nuclear fuels have tremendous potential to release vast amount of energy from fission reactions. Uranium is one of the most important nuclear fuels used in nuclear power plants. When uranium is bombarded with neutrons, fission reactions take place, releasing neutrons and tremendous amounts of energy. In 1942 Enrico Fermi used uranium to produce the first controlled chain reaction. The fission of uranium atoms in the reactor imparts the heat to produce steam for the generation

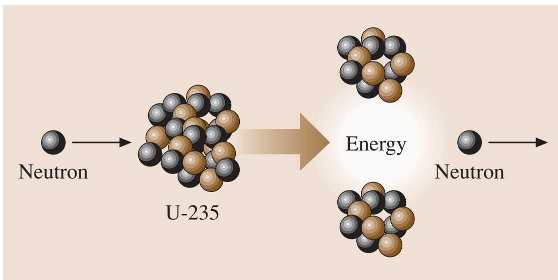

Fig. 16.11 Fission of a uranium 235 nucleus

electricity. When one pound of pure uranium is completely fissioned, it creates as much energy as burning of 1500 short tons of coal.

16.9.1 Basic Principles of Nuclear Energy

The powerful theory used to estimate the amount of energy released in a fission process is Albert Einstein's theory of relativity. Einstein's theory of relativity states that,

$$E = mc^2 , \tag{16.24}$$

where E is the energy in a substance, which equals the mass (m) of that substance multiplied by the speed of light squared (c^2). Nowadays most nuclear reactors are of fission type. In nuclear fission, the nuclei of atoms are split, causing energy to be released. The element uranium is the main fuel used in nuclear fission to produce energy since it has many useful properties: uranium nuclei can easily be split by shooting neutrons at them, and multiple neutrons released during this process are used to split other uranium, nuclei as shown in Fig. 16.11. This phenomenon is known as a chain reaction.

16.9.2 Types of Nuclear Power Plants

Nuclear power plants are classified according to the type of reactor used.

Fission Reactors

Fission power reactors generate heat by the nuclear fission of fissile isotopes of uranium and plutonium.

Various types of nuclear reactors are used in practice for power plants, which may be categorized into three classes:

- *Thermal reactors* use a neutron moderator to slow down or *moderate* the rate of production of fast neutrons by fission, to increase the probability that they will produce fission and thus sustain the chain reaction.
- *Fast reactors* sustain the chain reaction without the need for a neutron moderator.
- *Subcritical reactors* use an outside source of neutrons.
- Light-water reactor (LWR):
  - Pressurized-water reactor (PWR)
  - Boiling-water reactor (BWR)
- Graphite-moderated reactor:
  - Magnox
  - Advanced gas-cooled reactor (AGR)
  - Chernobyl type
  - Pebble-bed reactor (PBMR)
- Heavy-water moderated reactor:
  - CANDU (CANadian Deuterium Uranium)

16.10 Combined Power Station

When two cycles are combined, the cycle operated at the higher temperature is called the *topping cycle*. The waste heat it produces is then used in a second process that operates at a lower temperature level and is therefore called the *bottoming cycle* [16.4]. A combined cycle system is a sandwich of two different cycles,

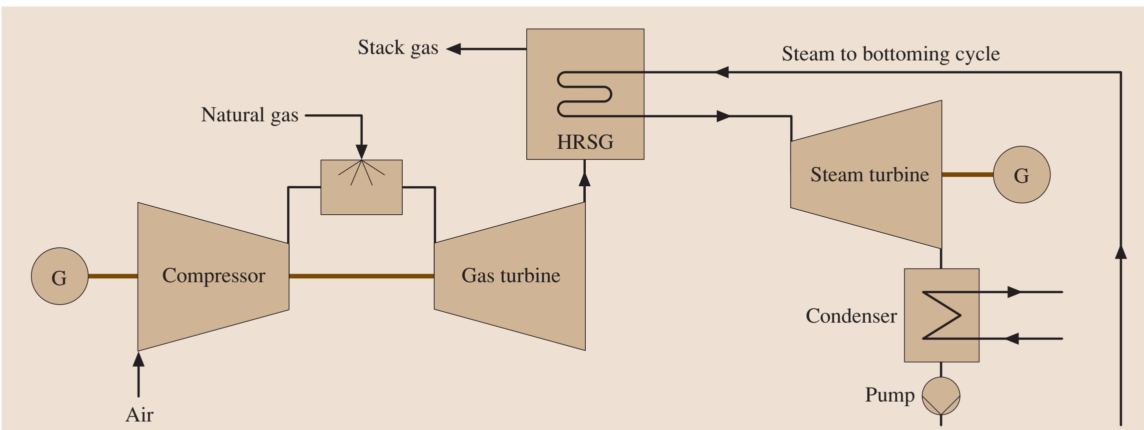

Fig. 16.12 Schematic diagram of a combined-cycle power plant

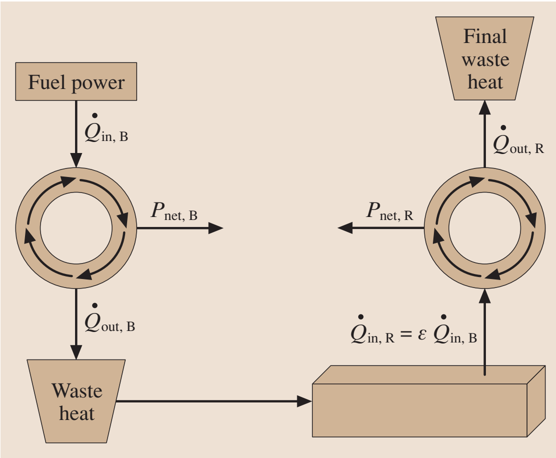

Fig. 16.13 Analysis of the combination of two different cycles

normally gas turbine and steam turbine cycles. The combination of two different cycles with different working media is interesting because the advantages of one complement the other [16.5].

The simplest form of combined cycle power plant, as shown in Fig. 16.12, is a single-pressure system. The major components present in the cycle is a single-pressure heat recovery steam generator (HRSG), a steam turbine, a water-cooled condenser, and a deaerater. The air is compressed inside the compressor and is supplied to the combustion chamber. The fuel (natural gas) from the main supply line is compressed in gas compressors and injected into the combustion chamber. The air and fuel mix together and then the combustion products leave the combustion chamber.

The combustion products from the combustion chamber enter the gas turbine and there expand to a low pressure and hence power is produced. The exhaust gas leaving the gas turbine is then supplied to the heat-recovery steam generator.

In the HRSG water flows in the direction opposite to the exhaust gas leaving the gas turbine and hence heat transfer takes place between the two fluids. The water absorbs heat from the exhaust gas, turns into steam, is superheated, and is then supplied to the steam turbine.

16.10.1 Thermodynamic Analysis of the Combined Cycle System

From Fig. 16.13 the net power output of the Brayton cycle is

$$P_{net,B} = \eta_B \dot{Q}_{in,B} \,, \tag{16.25}$$

where η_B is the Brayton efficiency.

The rate of heat rejected in the Brayton cycle is

$$\dot{Q}_{out,B} = (1-\eta_B)\dot{Q}_{in,B} \,. \tag{16.26}$$

The rate of heat input to the Rankine cycle is

$$\dot{Q}_{in,R} = \varepsilon \dot{Q}_{out,B} = \varepsilon(1-\eta_B)\dot{Q}_{in,B} \,, \tag{16.27}$$

where ε is the effectiveness.

The net power output of the Rankine cycle is

$$P_{net,R} = \eta_R \dot{Q}_{in,R} = \eta_R \varepsilon(1-\eta_B)\dot{Q}_{in,B} \,, \tag{16.28}$$

where η_R is the Rankine efficiency.

The net power output of the combined cycle is

$$P_{tot} = P_{net,B} + P_{net,R} \,, \tag{16.29}$$

$$P_{tot} = \eta_B \dot{Q}_{in,B} + \eta_R \varepsilon(1-\eta_B)\dot{Q}_{in,B} \,. \tag{16.30}$$

Overall Efficiency of the Combined Cycle Power Plant

The overall efficiency is defined as the ratio between the total power output to the heat added to the system

$$\eta_{ov} = \frac{P_{tot}}{\dot{Q}_{in,B}} \tag{16.31}$$

$$\eta_{ov} = \frac{\eta_B \dot{Q}_{in,B} + \eta_R \varepsilon(1-\eta_B)\dot{Q}_{in,B}}{\dot{Q}_{in,B}} \tag{16.32}$$

$$\eta_{ov} = \eta_B + \eta_R \varepsilon(1-\eta_B) \,. \tag{16.33}$$

16.11 Integrated Gasification Combined Cycle (IGCC) System

16.11.1 Introduction

IGCC technology is a promising technology which includes the benefit of gasification. A variety of fuel such as bituminous coal, sub-bituminous coal, lignite, petroleum coke, heavy oil, orimulsion, and biomass can provide the input to the IGCC cycle. Figure 16.14 shows the layout of integrated gasification combined cycle. Any grade of coal is gasified under pressure in the gasifier.

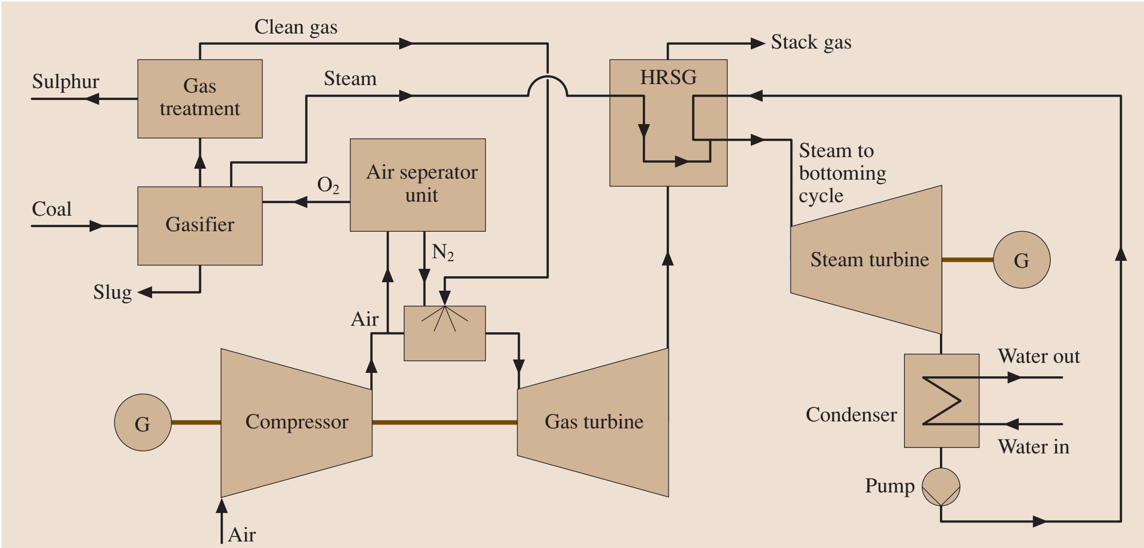

Fig. 16.14 Layout of an integrated gasification combined-cycle power plant

Syngas from the gasifier is cleaned of its hydrogen sulfide, ammonia, and particulate matter and is fed into a gas turbine where it is mixed inside the combustion chamber with hot pressurized air from the compressor. The final hot combustion products drive the gas turbine. The hot combustion gases from the gas turbine are used to produce steam in the steam generator. The steam drives the steam turbine, which produces 30–40% of the total electricity output. An air separation unit is also employed in modern IGCC power plants. Nitrogen and oxygen are completely separated in the air separator, from which pure oxygen is fed into the gasifier to reduce carbon dioxide emissions and the inert gas nitrogen is very well utilized in the gas turbine.

The technology makes use of the thermodynamic advantages provided by combining two different cycles: a gas turbine cycle and steam turbine cycle. Cleaning the gas before combustion provides benefits over the treatment of flue gases: a much smaller quantity of gas has to be treated and in addition the composition of the coal gas is such that it allows easier purification. The purification process could possibly be extended and could also permit the elimination of exhaust carbon dioxide. Hence, this technology has been proposed as the basis for a low-CO_2-emission coal power plant with CO_2 capture. Ample gasification processes have to be selected and the integration and optimization of all the processes are crucial for the overall efficiency. Coal gas clean up is another critical issue.

16.11.2 Environmental Benefits

1. Coal that contains a higher sulfur content can be very well utilized in IGCC plant. During the coal gasification process the sulfur in the coal appears as hydrogen sulphide; capturing hydrogen sulphide is not a tedious task. In some IGCC plants the sulfur can be extracted in a form that can be sold commercially.
2. Likewise, nitrogen typically exits as ammonia and can be scrubbed from the coal gas by processes that produce fertilizers or other ammonia-based chemicals.
3. If oxygen is used in a coal gasifier instead of air, carbon dioxide is emitted as a concentrated gas stream. In this form, it can be captured more easily and at lower costs for ultimate disposition in various sequestration approaches.

16.11.3 Efficiency Benefits

Efficiency gain is another benefit of IGCC plants. The fuel efficiency of IGCC power plant can be boosted to 50% or more. Future insights that integrate a fuel cell could achieve even higher efficiencies, maybe in the 60% range, which is nearly twice the value of today's typical coal-fired power plants. Higher efficiencies translate into more economical electric power and potential savings for ratepayers. A more efficient plant also uses less fuel to generate power, meaning that

less carbon dioxide is produced. IGCC plants with the flexibility to produce chemicals such as ammonia and hydrogen along with electricity make this a promising technology for future generations.

16.11.4 The Science of Coal Gasification

Coal gasification involves the chemical reaction of coal, steam, and air or oxygen at high temperatures to produce a mixture of hydrocarbon gases, typically carbon monoxide, carbon dioxide, and methane as well as hydrogen sulfide.

16.11.5 Chemical Reactions

Coal combustion, which is the exothermic reaction of coal with oxygen or air to produce carbon dioxide and water, is a fundamental part of coal gasification, using 20–40% of the oxygen or air required for complete combustion.

The purpose of this partial combustion is to supply the energy necessary to complete the gasification of the coal particles.

$$\begin{aligned}&\mathrm{C(s)}+\tfrac{1}{2}\mathrm{O_2}\rightarrow \mathrm{CO}\ \text{(partial combustion)}\,,\\&\Delta H_\mathrm{R}=-1110.5\,\mathrm{MJ/kmol}\,,\end{aligned}\tag{16.34}$$

where ΔH_R is the standard heat of reaction at 298 K and atmospheric pressure

This partial combustion reaction is exothermic, that is, it liberates heat, as signified by the negative sign.

Furthermore the reaction of carbon does not stop at CO_2, but any remaining oxygen rapidly reacts with CO in the gas phase to produce CO_2

$$\begin{aligned}&\mathrm{CO}+\tfrac{1}{2}\mathrm{O_2}\rightarrow \mathrm{CO_2}\,,\\&\Delta H_\mathrm{R}=-283.1\,\mathrm{MJ/kmol}\,.\end{aligned}\tag{16.35}$$

The solid carbonaceous material that is not combusted by oxygen reacts endothermically with carbon dioxide, hydrogen, and methane

$$\begin{aligned}&\mathrm{C}+\mathrm{CO_2}\rightarrow 2\mathrm{CO}\,,\\&\Delta H_\mathrm{R}=+172.0\,\mathrm{MJ/kmol}\,.\end{aligned}\tag{16.36}$$

This reaction is called the Boudouard reaction.

In order to control the high temperatures resulting from the C(s)-O_2 reactions, and to increase the heating value of the product gas through the production of hydrogen, steam is often added as a reactant.

$$\begin{aligned}&\mathrm{C(s)}+\mathrm{H_2O(g)}\rightarrow \mathrm{CO}+\mathrm{H_2}\,,\\&\Delta H_\mathrm{R}=+131.4\,\mathrm{MJ/kmol}\,.\end{aligned}\tag{16.37}$$

In a coal–steam or oxygen–steam, the homogeneous water-gas shift reaction is also important:

$$\begin{aligned}&\mathrm{CO}+\mathrm{H_2O(g)}\rightarrow \mathrm{CO_2}+\mathrm{H_2}\,,\\&\Delta H_\mathrm{R}=-41.0\,\mathrm{MJ/kmol}\,.\end{aligned}\tag{16.38}$$

Hydrogen is added as a reactant in order to increase the quantity of methane. Water gas from which the CO_2 has been removed is called *synthesis gas*. Synthesis gas can also be used to produce methane, or synthetic natural gas (SNG)

$$\mathrm{CO(g)}+3\mathrm{H_2(g)}\rightarrow \mathrm{CH_4(g)}+\mathrm{H_2O(g)}\,,\tag{16.39}$$

$$2\mathrm{CO(g)}+2\mathrm{H_2(g)}\rightarrow \mathrm{CH_4(g)}+\mathrm{CO_2(g)}\,.\tag{16.40}$$

In fuel-rich combustion, the sulfur in the coal is released mainly as hydrogen sulfide with a small amount of carbonyl sulfide and the fuel-bound nitrogen is released as elemental nitrogen, ammonia, and hydrogen cyanide.

In order to capture the sulfur, lime stone or dolomite may be fed to the gasifier

$$\mathrm{CaO}+\mathrm{H_2S}\rightarrow \mathrm{CaS}+\mathrm{H_2O}\,.\tag{16.41}$$

16.11.6 Optimal Coal Gasifiers

Gasifiers convert carbonaceous feedstock into gaseous products at high temperature and elevated pressure in the presence of oxygen and steam. Partial oxidation of the feedstock provides the heat. At operating conditions, chemical reactions occur that produce synthesis gas or *syngas*, a mixture of predominantly CO and H_2.

16.11.7 Classification of Gasifiers

A wide variety of gasifier designs has been developed for different applications and types of fuel used. The important parameters used for selecting the type of gasifiers are temperature, pressure, reactant gases, and the method of contacting. The different types of gasifier used in combined cycle technology are:

1. The entrained-flow (downflow) gasifier
2. The E-GAS entrained flow (up flow) gasifier
3. The Shell entrained flow (up flow) gasifier
4. The fluidized-bed gasifier
5. The transport reactor gasifier
6. The Lurgi dry ash gasifier
7. The British Gas/Lurgi fixed-bed gasifier
8. The Prenflo entrained bed gasifier

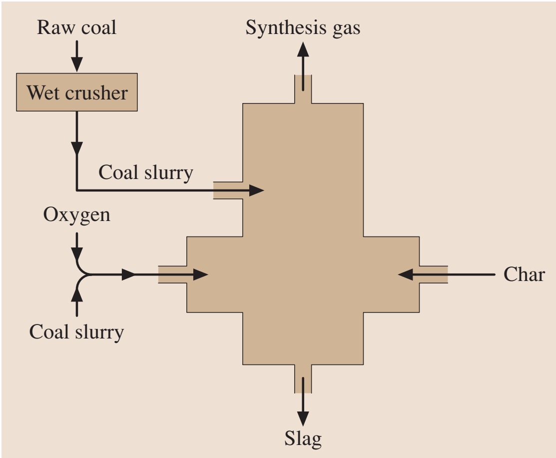

Fig. 16.15 E-GAS entrained-flow system

16.11.8 E-GAS Entrained Flow

Figure 16.15 shows the arrangement of the E-GAS entrained-flow gasifier. The gasification reaction occurs in two regions of the gasifier, normally called the primary and secondary. The raw feed coal is crushed in the wet crusher to produce slurries and is fed to the gasifier from the bottom portion normally called the first stage or the primary region of the gasifier. In this region exothermic gasification/oxidation reactions take place at a temperature of 1300–1400 °C, so great care has to be taken for the design. This region is normally lined with special slag-resistant refractory. There are two opposed horizontal burners with a horizontal cylinder provided in this region. Oxygen is used to gasify the slurry fed to the first stage of the gasifier. Usually 80% of the coal slurry is fed into this region. The remaining 20% of the coal slurry is injected into the hot raw gas coming out from the first stage.

The second stage contains a vertical cylinder that is perpendicular to the first stage. The endothermic gasification/devolatilization reactions in this stage reduce the final gas temperature and add some hydrocarbons to the product gas. Char is produced in the second stage. The hot gas leaving the gasifier is cooled in a fire-tube product gas cooler, generating saturated steam that is sent to the steam turbine.

16.12 Magnetohydrodynamic (MHD) Power Generation

16.12.1 Principle of MHD

The underlying principle of MHD power generation is elegantly simple. An electrically conducting fluid is driven by a primary energy source (e.g., the combustion of coal or a gas) through a magnetic field, resulting in the establishment of an electromotive force within the conductor in accordance with the principle established by Faraday [16.6].

Furthermore, if the conductor is an electrically conducting gas, it will expand, and hence the MHD system constitutes a heat engine concerning an expansion from high to low pressure in a manner similar to that of a gas turbine. Unlike gas turbine which involves surface interaction, the MHD system, however, involves a volume interaction between a gas and the magnetic field through which it is passing.

16.12.2 General Characteristics

The MHD generator can properly be viewed as an electromagnetic turbine because its output is obtained from the conducting gas–magnetic field interaction directly in electrical form rather than in mechanical form. Electrical conduction in gases occurs when electrons are available to be organized into an electric current in response to an applied or induced electric field. The electrons may be either injected or generated internally, and, because of the electrostatic forces involved, they require the presence of corresponding positive charge from ions to maintain electrical neutrality. An electrically conducting gas consists in general of electrons, ions to balance the electric charge, and neutral atoms or molecules; such a gas is termed a plasma [16.7].

16.12.3 The Production of Plasma

In MHD generators, electrons to support the flow of current can be obtained by two different methods: thermal and nonequilibrium ionization.

16.12.4 Thermal Ionization

Plasma is obtained by heating the gas to a sufficiently high temperature to yield electrons through ionization.

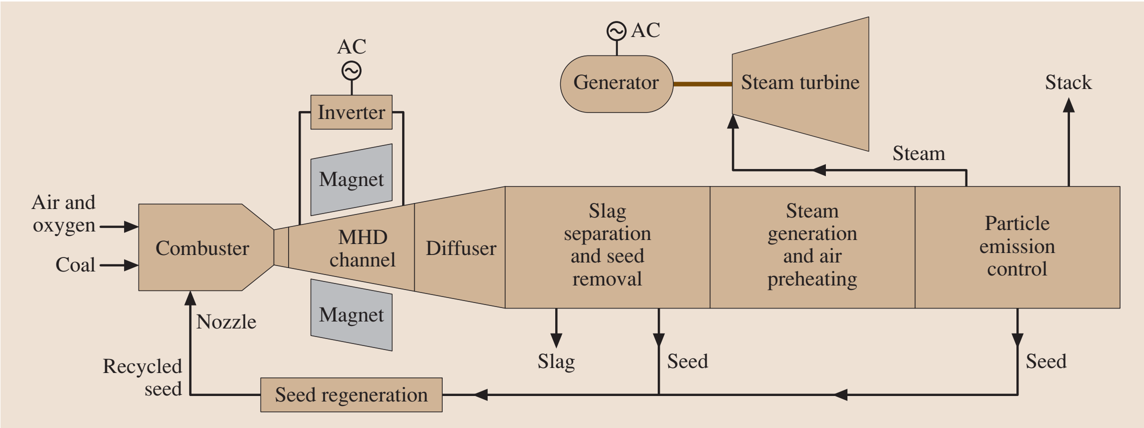

Fig. 16.16 Schematic view of an MHD steam power plant

16.12.5 Nonequilibrium Ionization

Sufficiently strong electric fields are induced in a manner similar to that in gas discharge devices. In either case, the mechanism of energy transfer from the flowing fluid to the electrical output can be thought of as a coupling of the electron-containing gas to the ions through electromagnetic forces. The ions in turn are embedded in the background of an atomic or molecular gas and lack mobility by virtue of their being coupled to the molecules or ions through collision processes described by kinetic behavior.

16.12.6 MHD Steam Power Plant

A schematic diagram of an MHD steam power plant is shown in Fig. 16.16. The product gas with a high electrical conductivity formed by burning the coal in the combustor is mixed with potassium carbonate (called seed) to increase its conductivity. The ionized gas then flows through a strong magnetic field, inducing an electric field and setting up a potential difference between the walls of the duct. Then using a solid-state inverter, the direct current (DC) generated is converted to alternating current (AC).

After flowing through the magnetic field, the hot gasses are then used to generate steam and turn a turbine as in a conventional plant. As the heat is transferred, slag is removed for disposal and the seed is captured for recycling. One considerable drawback is the need to use expensive superconducting magnets that must be cooled to $-269\,°C$ (4 K) to generate the necessary magnetic fields. About 50% of efficiency can be achieved if the MHD generator is operated in tandem with a conventional plant.

16.13 Total-Energy Systems for Heat and Power Generation

16.13.1 Cogeneration

A plant producing both electrical power and process heat simultaneously is called a cogeneration plant. The generation process can be any amalgamation of two different forms of useful energy (electricity and heat). Loss of energy in the condenser is very well utilized to obtain the required amount of heat, as the efficiency of a cogeneration system is higher than a conventional system operating in condensing mode. The heat obtained from a cogeneration plant is used for space heating of buildings, drying, to produce hot water or steam, or in various industrial processes.

The different types of cogeneration technologies are:

1. Steam turbine (ST) cogeneration system
2. Gas turbine (GT) cogeneration system
3. Combined cycle gas turbine (CCGT) cogeneration system
4. Internal combustion engine cogeneration system

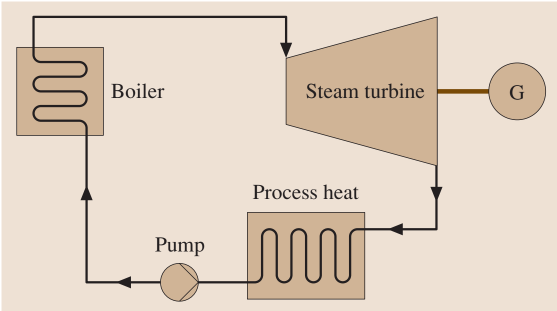

Fig. 16.17 Layout of a back-pressure turbine

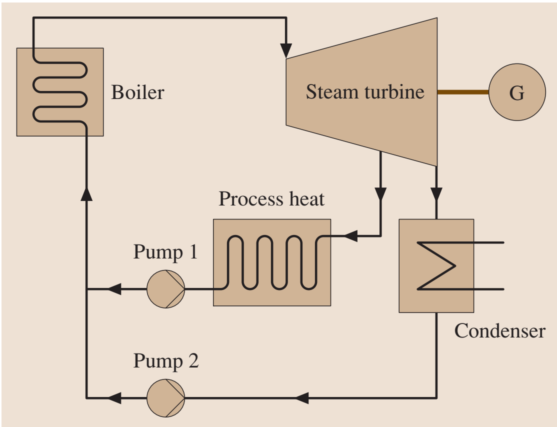

Fig. 16.18 Extraction condensing turbine

Steam Turbine Cogeneration System

Figure 16.17 depicts the layout of a cogeneration with a back pressure turbine. This signifies generation of electricity and heat by means of steam, generated in boilers by burning a suitable fuel (fossil or nonfossil, e.g., biomass). The steam is sent to the back-pressure

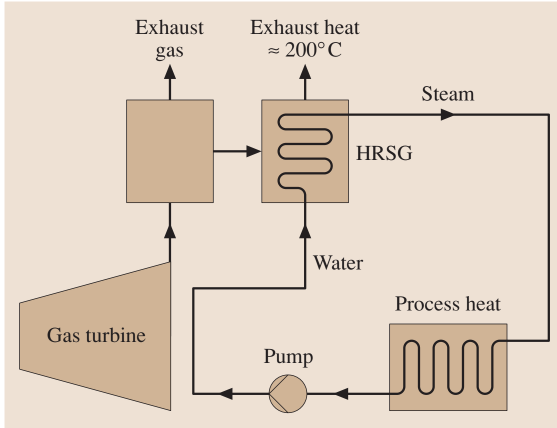

Fig. 16.20 Layout of an internal combustion engine cogeneration system

extraction turbine, where it is expanded until its designed back pressure. The steam turbine coupled with electric generators drives the steam turbine and produces electricity. Normally in cogeneration the required amount of heat is obtained by energy from the outlet of the steam turbine, from the back-pressure outlet or from the extractions of the steam turbine depicted in Figs. 16.17 and 16.18. The required thermal energy is delivered in the form of steam at a pressure corresponding to the design or with the required temperature in accord with the thermal energy level.

Gas Turbine Cogeneration System

In this design, a combination of gas and steam turbines is installed to convert energy from fuel to mechanical energy to drive electric generators.

Figure 16.19 represents the layout of a gas turbine cogeneration system. Hot gases from the gas turbine are

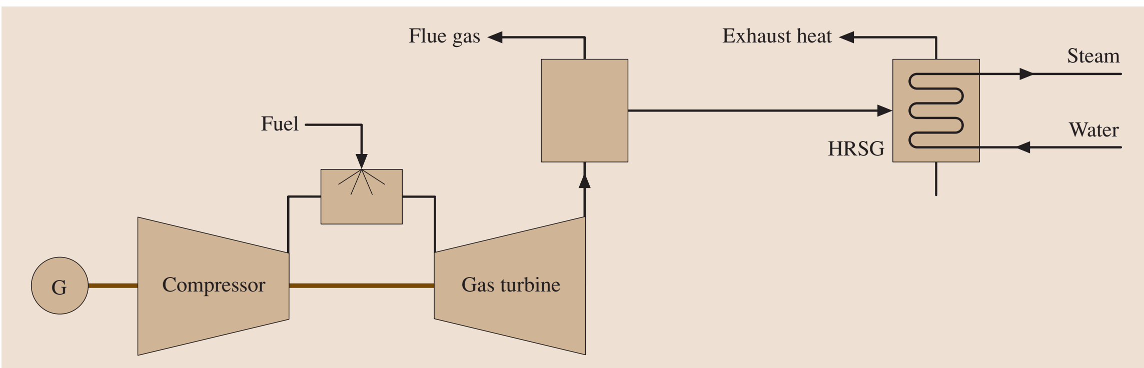

Fig. 16.19 Layout of a gas turbine cogeneration system

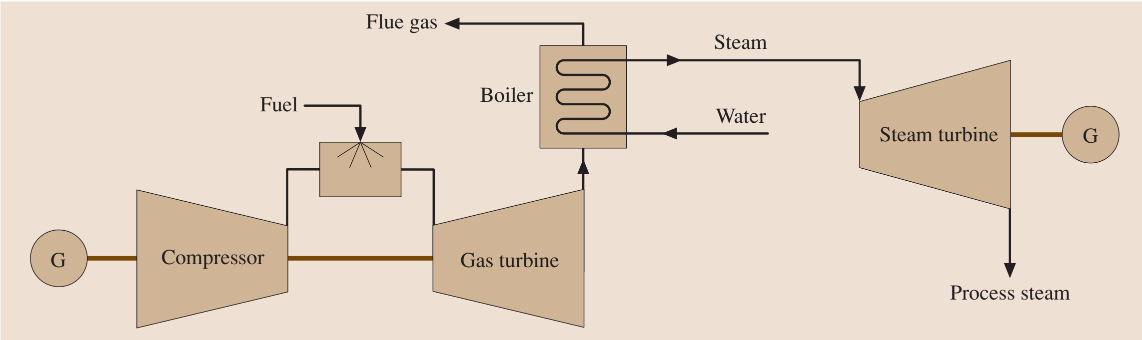

Fig. 16.21 Layout of a combined-cycle cogeneration system

used to generate steam for the steam turbine. Heat energy of the steam escaping from the turbine is used to provide heat. Mechanical energy (gas turbine and steam turbine) is converted into electrical energy with the help of a generator. The net efficiency of the plant is more than 50%.

Internal Combustion Engine Cogeneration System

Combined heat and power (CHP) systems are also available to serve smaller-sized facilities. In this type of facility, these smaller *modular* cogeneration units can generate 20–650 kW, and produce hot water from engine waste heat. Figure 16.20 represents the layout of an internal combustion engine cogeneration system. The generator converts mechanical work produced at the engine shaft into electrical energy. Heat resulting from combustion during power generation is used for process heat supply or heating purposes. Exhaust gases and the engine cooling water function as heat sources.

Combined Cycle Cogeneration System

Figure 16.21 represents the layout of a combined cycle cogeneration system. The combined cycle cogeneration system consists of a gas-turbine-driven generator package, a heat recovery steam generator closely matched to the process steam conditions, and a steam turbine matched to the HRSG's output and connected to the generator.

The advantages of this design are:

1. High thermal efficiency
2. Operating flexibility
3. Low installation cost

16.14 Transformation of Regenerative Energies

16.14.1 Wind Energy Power Plant

Wind is essentially created by solar heating of the atmosphere. Wind as a power source is attractive because it is plentiful, inexhaustible, and nonpolluting. Furthermore, it does not impose an extra heat burden on the environment [16.8]. Unfortunately, it is nonsteady and unreliable. Control equipment has been devised to start the wind power plant whenever the wind speed reaches 30 km/h. Methods have also been found to generate constant-frequency power with varying wind speeds and consequently varying speeds of windmill propellers. Wind power may prove practical for small power needs in isolated sites, but for maximum flexibility, it should be used in conjunction with other methods of power generation to ensure continuity [16.9]:

1. Small generators (0.5–10 kW) for isolated single premises
2. Medium generators (10–100 kW) for communities
3. Large generators (1.5 MW) for connection to the grid

Figure 16.22 depicts the arrangement of a wind turbine. The wind power is a measure of the energy available in the wind and is a function of the cube (the third power) of the wind speed. If the wind speed is doubled, the power in the wind increases by a factor of eight, so small differences in wind speed lead to large differences in electric power. This example points out that minor differences in wind speed due to either site selection or measurement errors can have a major bearing on a decision to invest in a wind turbine. For this

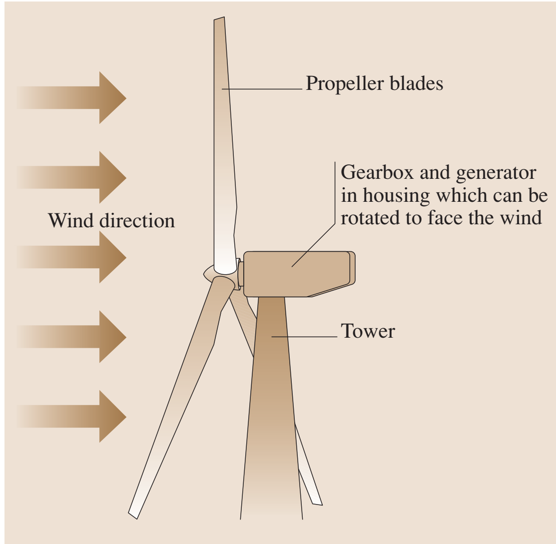

Fig. 16.22 Schematic view of the conversion of wind energy into electrical power ▶

reason, a thorough and accurate wind study is imperative before buying a wind turbine.

The theoretical power in a wind stream is given by

$$P = 0.5\rho A V^3 \quad (\mathrm{W})\,, \qquad (16.42)$$

where ρ is the density of air (1201 g/m^3 at normal temperature and pressure (NTP), V is the mean air velocity (m/s), and A is the swept area (m^2).

This equation states that the power is equal to one-half of the air density times the rotor area, times the cube of the wind speed. Moreover the air density varies due to the following features:

1. Elevation
2. Temperature
3. Weather fronts

16.15 Solar Power Stations

The sun acts as an atomic furnace as it converts mass into a huge amount of energy, according to Einstein's mass–energy relation $E = mc^2$. Every second it converts over 657 million tons of hydrogen into 653 million tons of helium, producing energy by nuclear fusion. The remaining 4 million tons of mass is discharged into space as energy. The Earth accepts only about one two-billionths of this. The radiation energy from the sun is massive, within 15 min the sun radiates energy equivalent to the amount of energy mankind consumes during a whole year. It is imperative to utilize this energy radiated by the sun, in order to fulfill our energy requirement.

16.15.1 Significant Features of Solar Energy

Ultimately solar energy is free and results in no hazard to the environment. In sunny countries, solar power can be used where there is no easy way to supply electricity to a remote place. It is also convenient for low-power devices such as solar-powered garden lights and battery chargers. There are various ways to produce electricity from the energy obtained from the sun.

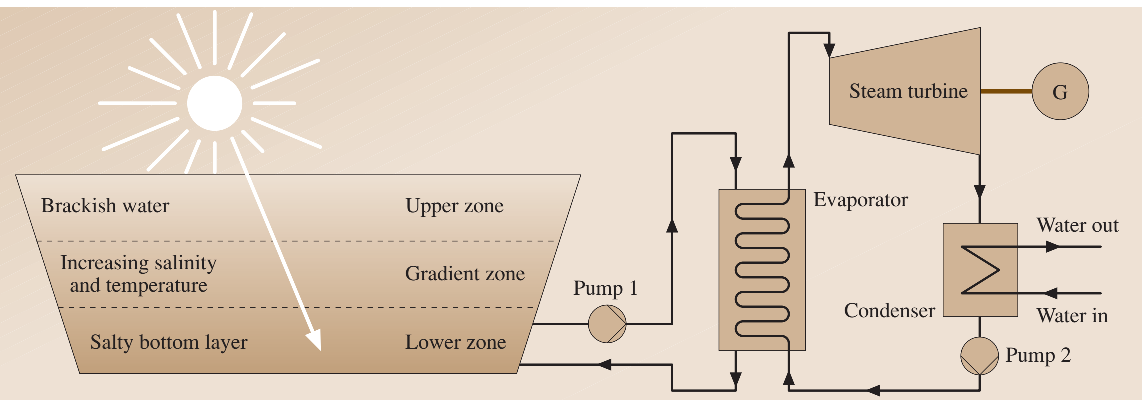

Fig. 16.23 Schematic of a solar pond

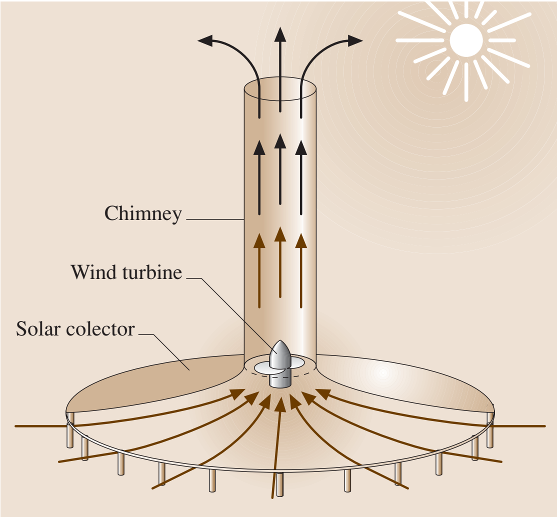

Fig. 16.24 Arrangement of a solar chimney

16.15.2 Solar Cells or Photovoltaic Cells

A solar panel is made up of the natural element silicon, which becomes charged electrically when subjected to sunlight. Sunlight is composed of packets of energy called photons. These photons contain various amounts of energy corresponding to the different wavelengths of light. The solar cell is made up of a material with well-defined possible energy levels for electrons. When a photon is absorbed in the active material, the energy of the photon is transferred to an electron, which becomes excited from a low to a higher energy level. The asymmetric structure of the solar cell ensures that this electron escapes from its normal position, carrying away the extra energy. This electron leaves the cell through a metal contact and becomes part of the current in an electrical circuit.

16.15.3 Solar Pond

A solar pond is a relatively low-tech, low-cost approach to harvest solar energy. A solar pond consists of three layers of water with different salt concentrations, as shown in the Fig. 16.23. A low-salt-content salt layer and an intermediate layer with a salt gradient, which creates a density gradient that averts heat exchange by natural convection in the water. The bottom layer with a higher salt content reaches a temperature of around 90 °C. The heat energy from the salty bottom layer can be used to generate electricity.

Normally an organic fluid with lower boiling point is used to convert this low-grade energy into electricity. The hot brine is pumped from the salty bottom layer and is sent into the evaporator, where it transfers heat to the organic fluid and the properly utilized brine is again sent to the salty bottom layer. The organic fluid in vapor form at the exit of the evaporator is used to rotate the turbine and generator.

The exhaust from the turbine is condensed in the condenser and then pumped back to the evaporator and hence the cycle is closed. The efficiency of the overall system entirely depends on the salinity and purity of the pond, and normally it is quite difficult to maintain salinity and dirt-free condition.

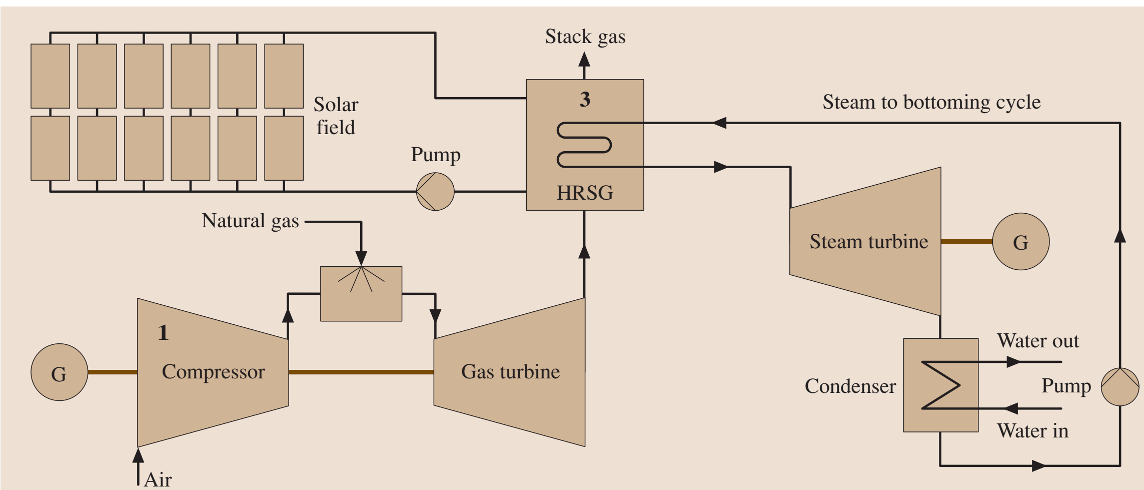

Fig. 16.25 Layout of an integrated solar combined cycle using a solar field

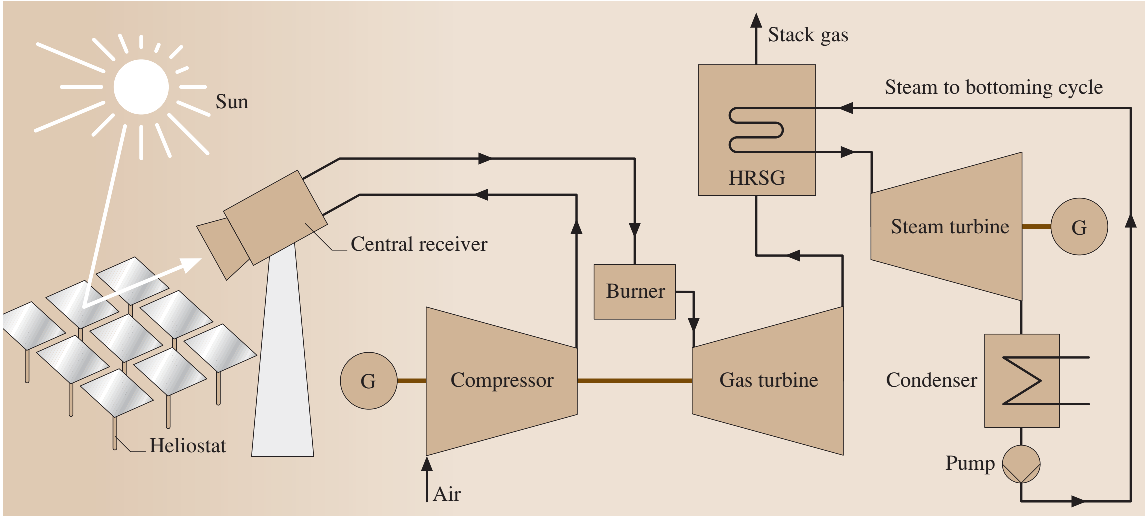

Fig. 16.26 Layout of integrated solar combined system using heliostats

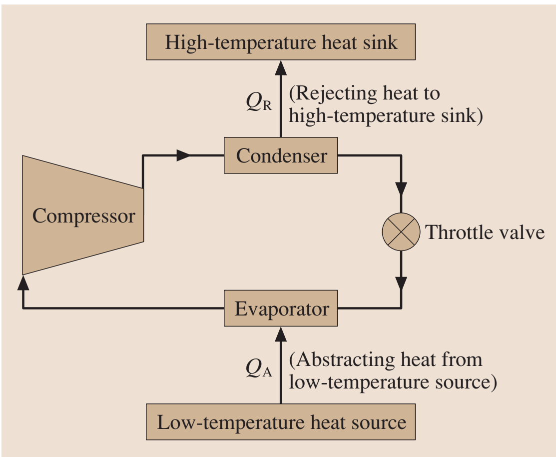

Fig. 16.27 Layout of a heat pump

16.15.4 Solar Chimney

Solar chimney technology is an innovative cost-effective technique to harness energy from the sun. A solar chimney consists of a glass collector, a wind turbine, an electrical generator, and a chimney. The glass collector is situated at the bottom and extends to a height of 2–7 m above the ground, as shown in the Fig. 16.24. The chimney is located at the center and its height varies from 500 to 1000 m. The conversion efficiency depends on the chimney height, the collector area, and the intensity of solar radiation.

The working principle of a solar chimney is quite simple: the air trapped inside the glass collector is heated by the radiation from the sun and becomes less dense, ascending the chimney. The rising hot air turns the wind turbine, which generates electricity.

16.15.5 Integrated Solar Combined Cycle Power System

Solar energy from a parabolic trough integrated in a combined cycle leads to high efficiency and low emission. Figure 16.25 shows the layout of this integrated solar combined cycle system. The heat from the parabolic trough collector can be directly utilized in the heat-recovery steam generator in addition to the heat supplied from the gas turbine exhaust. This integration seeks to achieve efficient operation even though solar energy intensity varies according to weather and time of day.

Sun-tracking concentrating mirrors called *heliostats* collect the sunlight and concentrate it onto a central receiver located at the top of a high tower, as shown in the Fig. 16.26. The receiver converts the radiative solar energy to thermal energy by heating air to the temperature required for direct feeding of the gas turbine.

Other possibilities for the exploitation of this energy can be endothermic chemical processes, or direct use of thermal energy for process heating. Central receiver technology is a promising alternative technology [16.10] overcoming the disadvantages of the trough technology.

16.16 Heat Pump

A reversed Carnot cycle can be used as heat pump. If the aim is to heat a body or space, the heat is rejected at a high temperature to the body or space and the heat is absorbed at a lower temperature from the ambient air or circulating water. Thus heat is drawn from the atmospheric air and pumped to the space to be heated. Such a cycle is called a heat pump cycle (Fig. 16.27) and the coefficient of performance (COP) for a Carnot reversed cycle heat pump is given by

$$\mathrm{COP}_{\text{Carnot heat pump}} = \frac{\text{Heat rejected}}{\text{Work done}} ,$$

$$\mathrm{COP}_{\text{Carnot heat pump}} = \frac{T_2}{T_2 - T_1} ,$$

where T_1 and T_2 are temperatures of source and sink.

The efficiency of this device to transfer heat Q_R to a high-temperature body is

$$\text{Efficiency} = \frac{\text{Energy effect sought}}{\text{Energy input}} .$$

16.17 Energy Storage and Distribution

Energy storage plays an important role in the competent management of energy resources. The demand for electricity fluctuates with time, which affects the economics of power plants that are normally designed for higher capacity.

The ultimate aim of an energy storage device is to reduce the economic losses due to fluctuating demand. When the demand is lower than the capacity, energy is stored. When the demand is higher than the capacity, the stored energy is released. This will provide savings in operating cost and ensure complete customer satisfaction, which can improve the status of the organization in the international market. Finally, energy storage is commonly used in stand-alone applications, where it can serve as an uninterruptible power supply (UPS) unit. The most important energy storage technologies are:

1. Pumped hydro power
2. Compressed energy storage
3. Flywheels
4. Electrochemical storage devices
5. Thermal energy storage devices
6. Secondary battery energy storage

16.17.1 Pumped Hydro Power

Pumped hydro facilities consist of two large reservoirs, one located at the base level and the other located at a different elevation. In pumped hydro, surplus power is utilized to pump the water from the lower reservoir to the upper reservoir, where it can be stored as potential energy. During periods of higher demand, water is sent back into the lower reservoir, passing through hydraulic turbines that generate electrical power [16.11]. The only drawback in pumped hydro power devices is that their construction cost is very high.

The combined efficiency of a pumped hydro system is given by

$$\eta_{\text{comb. effic.}} = \frac{\text{Total energy output}}{\text{Total energy input during a charge–discharge cycle}} . \tag{16.43}$$

16.17.2 Compressed Air Energy Storage

Excess energy is used to compress air and store it an airtight underground storage cavern. The stored energy is then released during periods of peak demand by expansion of the air through an air turbine. Three types of reservoirs can be used to store compressed air: salt caverns, aquifers, and hard rock caverns. When air is compressed for storage, its temperature increases according to

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} , \tag{16.44}$$

where n is the polytropic index, and P_1, T_1 and P_2, T_2 are the pressures and temperatures before and after compression.

Various studies have concluded that compressed air energy storage is competitive with combustion turbines and combined-cycle units, even without taking into account its unique benefits in terms of energy storage [16.12].

The layout of compressed energy storage device is shown in the Fig. 16.28. The heat of compres-

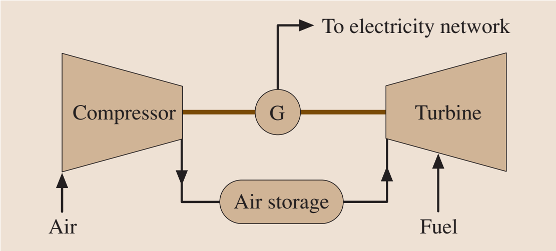

Fig. 16.28 Layout of compressed air storage

sion may be retained in the compressed air. This is called adiabatic storage and results in high storage efficiency, since more energy is recovered by expansion.

16.17.3 Energy Storage by Flywheels

Flywheel energy storage is a promising technology for providing intermediate energy storage. A flywheel storage device consists of a flywheel that rotates at a very high velocity and an integrated electrical apparatus that can operate either as a motor to turn the flywheel and store energy or as a generator to produce electrical power on demand using the energy stored in the flywheel. The use of magnetic bearings and a vacuum chamber helps reduce energy losses.

In a flywheel, energy storage is in the form of mechanical kinetic energy. The rotating mass stores the energy input so that the rotation can be maintained at a fairly constant rate. There are two main sources of losses in the flywheel: windage and bearing.

The energy stored in flywheel is

$$KE_{disc} = \frac{1}{4} M r^2 \omega^2 , \tag{16.45}$$

where M is the mass of the flywheel, and r is the radius of the flywheel.

In order to achieve high energy density, the rotation speed ω must be very high.

16.17.4 Electrochemical Energy Storage

Electrochemical energy storage is one of the recent technologies, which can be classified into three categories: primary batteries, secondary batteries, and fuel cells. These devices convert stored chemical energy into electrical energy. Primary and secondary batteries utilize the chemicals built into them, whereas fuel cells use chemically bonded energy supplied from the outside in the form of synthetic fuel [16.13].

16.17.5 Thermal Energy Storage

Thermal energy storage is ideally suited for applications such as space heating, where a low quantity of heat is required. The two distinct thermal energy storage mechanisms are sensible heat storage and latent heat storage. In sensible heat storage, energy can be stored as sensible heat by virtue of a rise in temperature of the storage medium.

16.17.6 Secondary Batteries

Large-scale battery use is almost unfeasible and their use is limited to battery-powered vehicles and storage for local fluctuating energy sources such as windmills or solar. The most widely used battery is the lead-acid battery, invented by Plante in 1859. The sodium-sulphur battery (200 W h/kg) and other combinations of materials are also being developed to obtain more output and storage per unit weight [16.9].

16.18 Furnaces

The furnace is the heart of a steam generation system. It is an enclosed chamber in which heat is produced by burning fuel, to heat water in the case of a steam generation system. Its dimensions and geometry are adapted to the amount of heat release, type of fuel, and to the method of firing so as to promote complete burning of the combustible and suitable disposal of the resulting ash. A furnace can provide combustion of fuel in solid, liquid or gaseous form.

Based upon the type of fuel used furnace are classified into:

1. Solid-fuel furnaces
2. Liquid-fuel furnaces
3. Gas-fuel furnaces

16.18.1 Combustion

Combustion or burning is a chemical process, an exothermic reaction between a substance (the fuel) and

a gas (the oxidizer), usually O_2, to release heat. The presence of CO_2 in the product gas signifies complete combustion whereas CO signifies incomplete combustion.

The basic chemical equations for complete combustion are

$$C + O_2 \to CO_2\,, \tag{16.46}$$

$$2H_2 + O_2 \to 2H_2O\,. \tag{16.47}$$

When the amount of oxygen supplied is insufficient for complete combustion then carbon will be burned incompletely with the formation of carbon monoxide

$$2C + O_2 \to 2CO\,. \tag{16.48}$$

The most important parameter to estimate the effectiveness of combustion is called the combustion efficiency, which depends on the following parameters:

1. Air–fuel ratio
2. Fuel–air mixing
3. Flame temperature
4. Flame shape
5. Fuel residence time
6. Degree of atomization (for liquid fuel)
7. Degree of turbulence

The theoretical air–fuel ratio for complete combustion is known as the stoichiometric ratio. In practice every oxygen molecule does not come into contact with a fuel molecule. In order to ensure complete combustion some amount of air is used to compensate this shortage of oxygen molecules, normally called *excess air*, and attain complete combustion. Turbulence enhances the proper mixing of fuel and oxygen and hence the combustion efficiency.

16.18.2 Ideal Combustion

The generalized ideal combustion equation can be written as

$$\begin{aligned} &C_XH_YS_ZO_K + \left(X + \frac{Y}{4} + Z + \frac{K}{2}\right) O_2 + mH_2O \\ &\to PCO_2 + QH_2O + GSO_2\,. \end{aligned} \tag{16.49}$$

The generalized combustion equation can be written

$$\begin{aligned} &C_XH_YS_ZO_K + \left(X + \frac{Y}{4} + Z + \frac{K}{2}\right) O_2 \\ &\quad + 3.76\left(X + \frac{Y}{4} + Z + \frac{K}{2}\right) N_2 + mH_2O \\ &\to PCO_2 + QH_2O + RN_2 + GSO_2\,. \end{aligned} \tag{16.50}$$

The air–fuel ratio can be written

$$\frac{A}{F} = \frac{m_{\text{air}}}{m_{\text{f}}}\,. \tag{16.51}$$

16.18.3 Theoretical Dry Air–Fuel Ratio

1 kmole of oxygen and 3.76 mole of nitrogen generate a mixture of 4.76 mole of air.

The molecular weight of air is therefore

$$\frac{32 + 3.76 \times 28}{4.76} = 28.84\,, \tag{16.52}$$

$$\begin{aligned} \left(\frac{A}{F}\right)_{\text{TD}} &= \frac{m_{\text{air}}}{m_{\text{f}}} \\ &= \frac{4.76\left(X + \frac{Y}{4} + Z - \frac{K}{2}\right) 28.84}{100}\,. \end{aligned} \tag{16.53}$$

16.18.4 Theoretical Wet-Air–Fuel Ratio

Ambient air is always humid in nature so the calculation of the theoretical wet-air–fuel ratio depends on the relative humidity. The specific humidity of air, w (kg) of moisture per kg of dry air.

Relative humidity

$$\phi = \frac{p_{\text{vapor,act}}}{p_{\text{vapor,sat}}}\,. \tag{16.54}$$

Amount of moisture in ambient air

$$n = \frac{4.76\,(X + Y/4 + Z - K/2)\,28.84w}{18}\,. \tag{16.55}$$

Theoretical wet-air–fuel ratio

$$\begin{aligned} \left(\frac{A}{F}\right)_{\text{TW}} &= \frac{m_{\text{wet,air}}}{m_{\text{f}}} \\ &= \frac{\left[4.76\left(X + \frac{Y}{4} + Z - \frac{K}{2}\right)\right](28.84 + w18)}{100}\,. \end{aligned} \tag{16.56}$$

16.18.5 Pressure Conditions

Not all boiler furnaces are airtight, especially stokers (boilers that burn solid fuels). Flue gases may escape into the plant area if the furnace pressure is greater than the atmospheric pressure. Other furnace designs may require draft and furnace pressure control. Typically, the furnace pressure is controlled using a balance draft system. The induced draft fan is modulated to maintain the

furnace at a slight negative pressure. Furnace pressure measurement and induced fan control is required. The location of the furnace pressure transmitter is important because the pressure is not uniform within the furnace. If the combustion airflow rate measurement is available, furnace pressure control can be more effective.

16.18.6 Emission

The combustion of fuel finally leads to the emission of various gases and particulate matter. The amount and chemical components of these emissions depend on the fuel type, boiler type and size, and the firing method. Different forms of emissions are described below.

16.18.7 Particulate Emissions

The particulates present in the stack gases depend primarily on the combustion efficiency and on the amount of ash contained in the fuel. All fuels except natural gas contain some quantity of ash or noncombustible material, which forms the majority of these particulates [16.14, 15].

16.18.8 Nitrogen Oxide Emission

The level of nitrogen oxides (NO_x) present in the stack gas depends on many variables; the furnace heat rate levels, temperature, and excess air are the major variables that affect NO_x emission levels. NO_x is one of the contributors to acid rain and ozone formation, visibility degradation, and human health concerns. Combustion of any fossil fuel generates some level of NO_x due to the high temperature and availability of oxygen and nitrogen from both the air and fuel. Based on the method of formation, NO_x can be classified as thermal NO_x and fuel NO_x.

16.18.9 Thermal NO_x

High-temperature oxidation (above 1200 °C) initiates the formation of NO_x, normally called thermal NO_x. The nitrogen and oxygen in the air dissociate at higher combustion temperatures and lead to the formation of NO_x. Thermal NO_x formation is typically controlled by reducing the peak and average flame temperature. Apart from a higher temperature, the formation of NO_x is also due to longer residence time and oxygen concentration. Three possible reactions for the formation of NO_x during combustion are [16.15]

$$N_2 + O \rightarrow NO + N\,, \tag{16.57}$$

$$N + O_2 \rightarrow NO + O\,, \tag{16.58}$$

$$N + OH \rightarrow NO + H\,. \tag{16.59}$$

16.18.10 Fuel NO_x

Fuel NO_x refers to the formation of chemically bound nitrogen in the fuel during combustion. The fuel–air ratio is one of the deciding factors for the formation of fuel NO_x. Conversion of fuel-bound nitrogen to NO_x is strongly dependent on the fuel–air ratio but is relatively independent of the combustion-zone temperature. The formation of NO_x happens at two levels, one is during oxidation of volatile nitrogen and another is from the char during combustion.

16.18.11 Sulfur Dioxide Emission

SO_2 is an acidic gas formed by the combustion of sulfur in the fuel with oxygen. Dilute sulfuric acid is a major constituent of acid rain. An aqueous solution of sulfurous acid (SO_3) is formed when sulphur dioxide combines with water. This can easily oxidize in the atmosphere to form sulfuric acid (H_2SO_4).

16.18.12 Solid-Fuel Furnaces

Furnaces that use solid fuels for combustion are normally called solid fuel furnaces. Fuels include, coal, coke, and firewood (wood chips and pellets).

16.18.13 Stokers and Grates

There are various ways to introduce coal into the furnace. Stokers play a vital role in distributing coal into the furnace. Stokers are normally differentiated on the basis of how the coal is introduced into the fire. Different types of stokers are:

1. Traveling-grate stoker
2. Chain-grate stoker
3. Spreader stoker
4. Vibrating stoker
5. Underfeed stoker

Traveling-grate stokers have been in use for the past 50 years and are the most popular way to burn coal in stokers for boilers. In addition to coal, traveling-grate

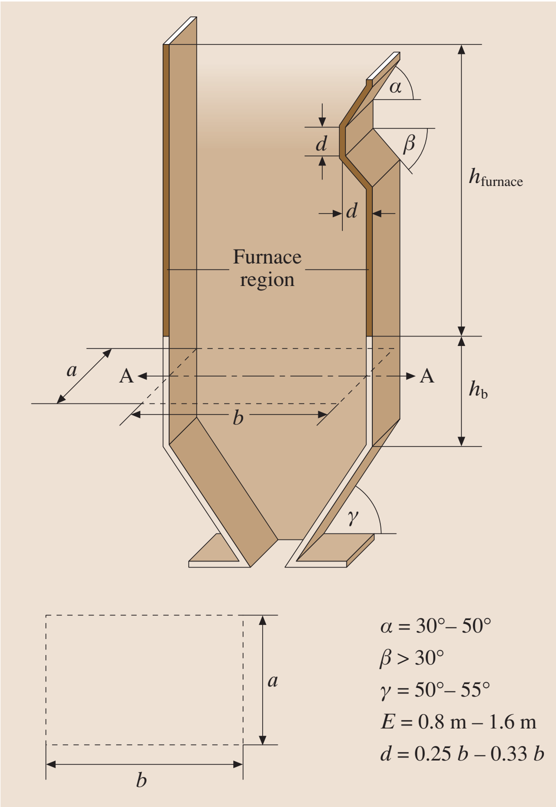

Fig. 16.29 Basic furnace geometry

stokers can handle a wide variety of waste fuels. Underfeed stokers are only used for small plants, and mainly for steam production rather than power generation. An underfeed stoker pushes the coal up into the furnace from below the grate.

Chain and traveling grate furnaces have similar characteristics. Coal lumps are fed continuously on to a moving grate or chain. Air is drawn through the grate and through the bed of coal on top. As the coal enters, it is heated by radiation from the refractory. Moisture and volatile matter are driven off. The chain/grate moves the coal slowly into the region in which ignition is established, and the temperature in the coal bed rises. The carbon gradually burns off, leaving ash which drops off at the end into a receptacle, from which it is removed for disposal. The ash formed may have a carbon content as high as 4–5 %.

In the spreader stoker arrangement, a high-speed rotor throws the coal into the furnace over a moving grate to promote fuel distribution.

16.18.14 Pulverized-Fuel Furnaces

The furnace is the most important part of a boiler. Its primary function is to provide sufficient space for fuel particles to burn completely and to cool the flue gas to a temperature at which the convective heating surfaces can be operated safely. Structurally the boiler furnace consists of the combustion space surrounded by water walls. The principle of combustion in pulverized-fuel boilers is that coal ground into a fine powder is mixed with air and transported into a combustion chamber where it is burnt in a flame similar to the flame of a liquid or gaseous fuel.

The furnace is designed to perform two functions simultaneously, namely:

- The release of the chemical energy of fuel by combustion: the first task of combustion technology is to burn the fuel efficiently and steadily, to consume controlled excess air (as little as possible).
- To generate a flame with a controlled shape that will generate the lowest amount of pollutants and ensure the transfer of heat from the furnace to the working fluid inside the water walls. The important task of furnace heat removal is to produce a controlled furnace exit gas temperature (FEGT). The FEGT is an important aspect of boiler safety.

The combustion gases leave the furnace at a safe temperature which will not cause clinkering to the subsequent heating surface.

A furnace can be characterized geometrically by its linear dimensions: the front width a, the depth b, and height h_{f} as mentioned in Fig. 16.29 which are estimated according to the rated fuel consumption and the thermal, physical, and chemical properties of the fuel to be used.

The furnace height should be sufficiently high that the flame should not heat the superheater tubes. Furnace width and depth are two of the most important parameters for design. The minimum value of furnace depth depends on the capacity of the boiler and types of fuel burnt.

The following factors influence the width and depth of the furnace:

1. The arrangement of burners
2. The heat release rate per unit furnace area
3. The power output of each burner
4. The flame length

Depending upon the condition of the ash leaving the bottom of the furnace, pulverized furnaces can be classified into two types:

1. Dry-bottom furnaces
2. Wet-bottom furnaces

16.18.15 Dry-Bottom Furnace

Dry bottom means that the boiler has a furnace bottom temperature below the ash melting point. In this furnace design ash or slag is removed in the dry state. In the dry-bottom type, ash falling down from the boiler furnace is conveyed by a continuously moving scraper chain conveyor to the clinker grinder, which is conveyed to the slurry sump through sloping trenches with the help of a high-pressure water jet. The furnace hopper dimension is one of the most important parameters for the effective removal of dry ash from the furnace. Normally the walls of the hopper are inclined at an angle of 48–60°.

16.18.16 Wet-Bottom Furnace

In a wet-bottom furnace ash or slag is removed in the wet state. In this design the hopper is filled with water and ash falling down is quenched and removed after a predetermined time with the help of a jet pumping system and conveyed to the slurry sump. This type of hopper is known as a water-impounded bottom ash hopper. There are two types of wet-bottom boilers: the slag-tap boiler and the cyclone boiler. The slag-tap boiler burns pulverized coal and the cyclone boiler burns crushed coal. In each type, the bottom ash is kept in a molten state and tapped off as a liquid. Both boiler types have a solid base with an orifice that can be opened to permit the molten ash that has collected at the base to flow into the ash hopper below. The ash hopper in wet-bottom furnaces contains quenching water. When the molten slag comes into contact with the quenching water, it fractures instantly, crystallizes, and forms pellets.

16.19 Fluidized-Bed Combustion System

Fluidized-bed combustion (FBC) technology is a very appropriate technology for efficient solid-fuel combustion. The velocity at which the bed behaves like a fluid is called fluidization velocity. At this point the pressure drop across the bed is equal to the weight of the particles per unit cross section of the bed. Increasing the air velocity imparts turbulent motion, which helps ensure proper mixing of the gas and particles.

Solid coal is crushed in the crusher to the required size, normally a mean particle diameter of around 0.5–12 mm, and fed into the fluidized bed, where it mixes with gas and inert materials and undergoes various reactions such as drying, devolatilization, combustion of volatiles, and the combustion of residual tar. During drying all the moisture present in the coal will be removed and the volatile matter is gradually released as the temperature increases; moreover the release of volatile matter is directly proportion to the temperature and inversely proportional to the gas pressure. After the volatile is released, combustion of the volatiles takes place, and finally burning of char takes place depending on the coal type, fluidization system, and char diameter.

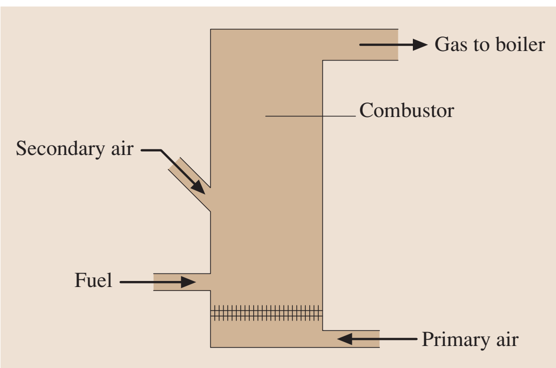

Fig. 16.30 Bubbling fluidized-bed combustion

Fluidization technique results in a vast improvement in combustion efficiency of high-moisture-content fuels, and is adaptable to a variety of waste-type fuels. The scrubbing action of the bed material on the fuel particle enhances the combustion process by shredding away the carbon dioxide and char layers that normally form around the fuel particle. FBC reduces the amount of sulfur emitted in the form of SO_x emissions. Limestone is used to precipitate out sulfate during combustion. FBC boilers can burn fuels other than coal, and the lower temperatures of combustion (800 °C) have other added benefits as well. FBC

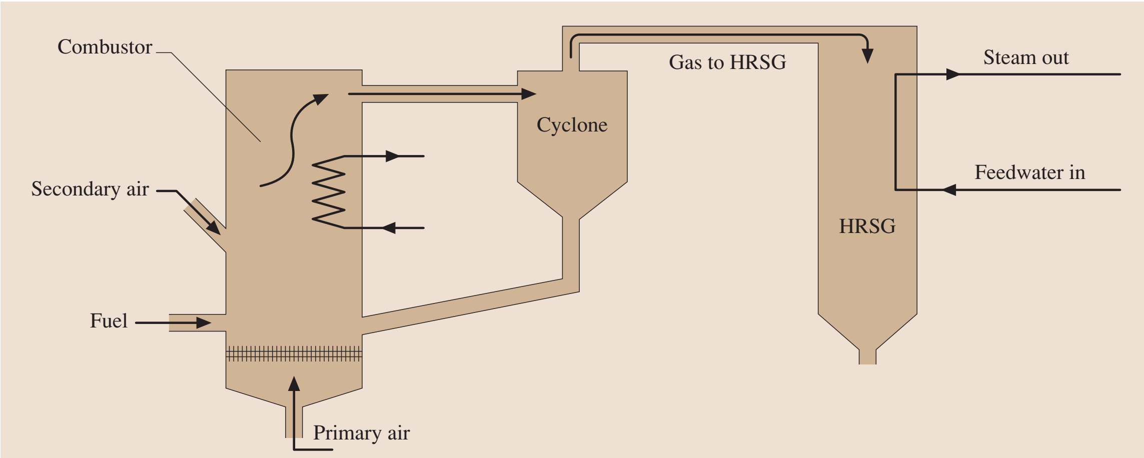

Fig. 16.31 Circulating fluidized-bed combustion

in boilers at atmospheric pressure can be particularly useful for high-ash coals, and/or those with variable characteristics.

Features of Fluidized-Bed Combustion Systems

Emissions from fluidized-bed combustor are always lower than conventional combustion technologies for the following reasons:

- Low combustion temperatures and low excess air within the fluidized bed reduces the formation of NO_x.
- High combustion efficiency results in flue gases that contain low amounts of CO.
- Emission such as SO_x may be abated within the fluidized-bed system by injecting limestone into the bed and ammonia into the vapor space.
- Fluidized-bed combustion is an environmentally favorable, proven technology for the disposal of solid wastes and the generation of energy.

16.19.1 Bubbling Fluidized-Bed Combustion

Bubbling beds use a low fluidizing velocity, so that the particles are held mainly in a bed with a definable surface. Inert materials are often used to improve the bed stability, together with limestone for SO_2 absorption. In-bed tubes are used to control the bed temperature and generate steam.

16.19.2 Circulating Fluidized-Bed Combustion

Generally circulating fluidized-bed combustion uses a boiler and a high-temperature cyclone. The gas velocity is as high as 4–8 m/s. Coarse fluidizing medium and char in the flue gas are collected by the high-temperature cyclone, and are recycled to the boiler as shown in Fig. 16.31. Air is introduced into the bed in two regions. About 40–70% of the air is injected through the nozzle grate at the bottom of the bed, normally called the primary air, and the remaining air, called the secondary air, is injected through nozzles on the side walls of the fluidized bed. The combustion proceeds in two zones: a primary reducing zone in the lower section of the combustor and an oxidizing zone in the upper part of the combustor where complete combustion is achieved through the use of excess air. This staged combustion, at controlled low temperatures, effectively suppresses NO_x formation. To increase the thermal efficiency, a preheater for fluidizing air and combustion air, and a boiler feedwater heater are installed.

16.20 Liquid–Fuel Furnace

Liquid fuels such as gasoline, kerosene, and diesel fuel are used directly for combustion in a liquid-fuel-fired furnace. Two major categories of fuel oil are burned by combustion sources: distillate oil and residual oil. Distillate oils are commonly used in domestic and small commercial applications, and include kerosene and diesel oil. Residual oil is mainly used in utility and large commercial application.

16.20.1 Special Characteristics

1. Due to the finer atomization (mean particle size 20 mm in the cause of fuel oil) better combustion takes place, resulting in a reduction in excess air requirement from 31% to 6%.
2. Liquid fuels having higher calorific value when compared to solid fuels.
3. These fuels occupy less space during storage.
4. These furnaces have practically no ash formation.

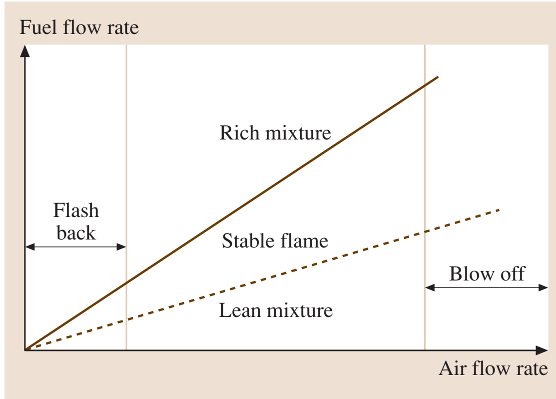

Fig. 16.32 Stability and flammability limits

5. The furnaces are easy to light up and shut down.
6. The furnaces have higher efficiency.
7. The fuel consumption rate can be controlled easily.

16.21 Burners

In order to achieve efficient combustion proper mixing of air and fuel is always necessary. The fuel must be evenly dispersed in the combustion airstream such that the fuel and air can make intimate contact. Failure to achieve this results in unburnt or partially burnt fuel. It is very important to design a component to achieve this task and provide better combustion efficiency. The burner is the apparatus for burning fuels continuously and more securely. The burner design attempts to achieve this using a variety of techniques. Important design criteria of burners are the burning rate, burning velocity, flashback, and the quenching diameter. Among these, the burning velocity is the deciding factor for the performance of the burner. It is defined as the relative velocity of the flame front to the unburned gases which is propagating normal to the flame front. These design parameters are related as follows

$$\text{burning velocity} > \text{flow velocity: flashback limit}\,,$$

$$\text{burning velocity} < \text{flow velocity: blow-off limit}\,,$$

$$\text{burning velocity} = \text{flow velocity: stable flame}\,.$$

The graph between the fuel flow rate and the airflow rate describes the mixing conditions, as shown in Fig. 16.32. The amount of air inflow affects the heat of the flame, and can be controlled by adjusting the slot openings. Stoichiometric calculation of the designed fuel determines the amount of air required, the fuel gas produced, and the heat released per unit weight of fuel burnt.

Minimum Air Required per Kilogram of Solid or Liquid Fuel Burnt

If a known mass of fuel consists of fractions of carbon, hydrogen, oxygen, and sulphur, then the minimum air required to burn the fuel is calculated as

For carbon requirement

$$= \text{mass of carbon (kg)} \times \left(\frac{8}{3\,\text{kg}}\right) \text{ of oxygen.}$$

For hydrogen

$$= \text{mass of hydrogen (kg)} \times 8\,\text{kg of oxygen.}$$

For sulphur

$$= \text{mass of sulphur} \times 1\,\text{kg of oxygen}\,.$$

Therefore, the amount of oxygen required for complete combustion of 1 kg of fuel is given by

$$\tfrac{8}{3}C + 8H_2 + S - O_2$$

$$= \tfrac{8}{3}C + 8\left(H_2 - \frac{O_2}{8}\right) + S$$

and atmospheric air contains 23 wt % of oxygen. Therefore, the minimum amount of air required per kilogram of fuel is

$$\frac{100}{23}\left(\frac{8}{3}C+8H_2+S-O_2\right)$$
$$=11.6C+34.8\left(H_2-\frac{O_2}{8}\right)+4.35S\,.$$

This is the theoretical amount of air required. The quantity of air in excess of this theoretical minimum that is actually required for complete combustion of the solid and liquid fuels is called the excess air.

16.21.1 Various Types of Burners

Burners can be classified in a number of ways: principle of operation (swirl type, parallel, or direct flow type), fuel (gaseous-fuel burners, liquid-fuel burners, and solid-fuel burners), and geometry (orifice burners, nozzle burners, flat flame burners, and burners with different shapes of openings).

16.21.2 Liquid-Fuel Burners

Fuel oil is the commonly used liquid fuel in the burners. An oil supply pump is provided to supply oil from the tank to the burner. To facilitate the fuel vaporization oil burners are designed to increase the contact surface area of the oil with air. To facilitate this, oil is atomized before entering the combustion chamber. It is difficult to atomize the fuel at ambient temperature so it has to be heated. this is achieved by single unit heating loops and a centralized heating system. A liquid fuel burner consists of a fuel supply line with a fuel atomizer, a concentric primary air supply with an air bag, and a secondary air supply with a vane control valve.

An oil burner is a mechanical device that combines fuel oil with appropriate amounts of air before delivering the mixture to the point of ignition in a combustion chamber. It is essential for the efficiency of the combustion process that the oil–air mixture is well homogenized and with as few pure droplets of fuel oil as possible. Fuel oil burners either vaporize or atomize the fuel oil.

Fuel oil burners can in general categorized into:

- Gun-type (atomizing) burners (pressure gun)
- Pot-type (vaporizing) burners
- Rotary-type fuel oil burners

16.21.3 Gun-Type Burners (Pressure Gun)

A gun-type burner atomizes the fuel oil by forcing the oil through a nozzle and spraying it into a gun-like airflow atomic nozzle. The liquid forms microscopic particles or globules that are well mixed and partly evaporated before being ignited in the combustion chamber. A residential gun-type burner normally requires a 551–896 kPa oil pressure. Commercial and industrial burners require 689–2068 kPa. The gun type is very flexible and can be used within a large range of

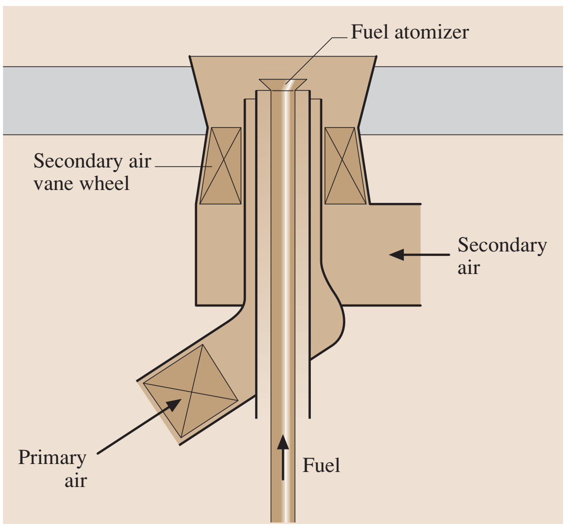

Fig. 16.33 Liquid-fuel burner arrangement

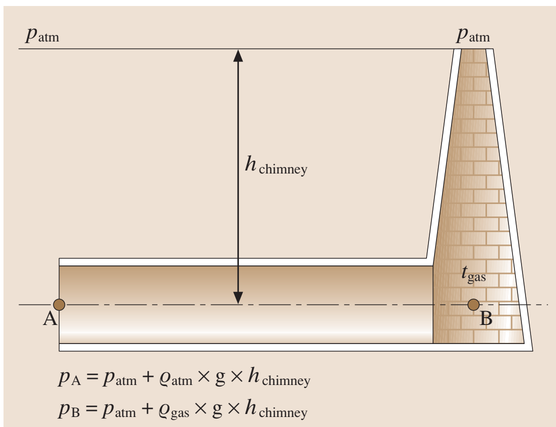

Fig. 16.34 Natural draught produced by a chimney

applications, from relative small residential heaters to larger industrial heating applications.

16.21.4 Pot-Type Burners

In a pot-type fuel burner the fuel evaporates into the combustion air. They are in general:

- Natural draft burners
- Forced draft burners
- Sleeve burners

In atmospheric pot-type heaters gravity causes the oil to flow to the burner. The natural draft burner relies on the natural draft in the chimney for air supply. The forced draft burner relies on a mechanical fan and/or the chimney for air supply. The perforated sleeve burner is only used in small applications. The pot-type burner is the most inexpensive of the fuel oil burners and has the lowest operating cost. A disadvantage of the pot-type is its limited capacity. This type is in general most suitable for smaller applications.

16.22 General Furnace Accessories

16.22.1 Fans

A fan moves a quantity of air or gas by adding sufficient energy to the stream to initiate motion and overcome resistance to flow. It helps to supply air for combustion, drying coal, and recirculation of gas.

16.22.2 Forced Draft Fan

The forced draft fan supplies combustion air and is important because it ensures adequate air–fuel mixing and keeps the flame away from the nozzle. The furnace operates under pressure and flue gases are exhausted by forced draft convection. The airflow rate is typically controlled with air dampers. Some applications use fan speed control.

16.22.3 Induced Draft Fan

The induced draft fan exhausts flue gases from the furnace and induces combustion air into the furnace by having the furnace operate under negative pressure. An induced draft fan can handle higher-temperature gas, which may contain corrosive ash.

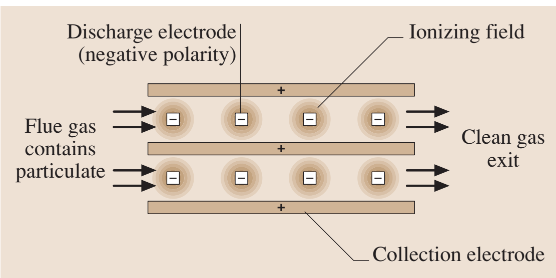

Fig. 16.35 Electrostatic precipitator (ESP), schematic diagram (top view)

16.22.4 Balanced Draft (BD)

The balanced draft design uses both forced draft and induced draft fans. It is used when the furnace design requires draft and furnace pressure control. Balance draft furnaces are typically operated at a slightly negative pressure, but they can also operate at slightly positive pressure. A furnace pressure measurement and induced fan control are required.

16.22.5 Primary Air Fans

In a coal-fired boiler, primary fans are used to supply the air needed to dry the coal and transport it to the boiler. Primary fans are usually located before or after the preheater.

16.22.6 Stacks

Stacks are used to create the required pressure differential for the flow of air and flue gas.

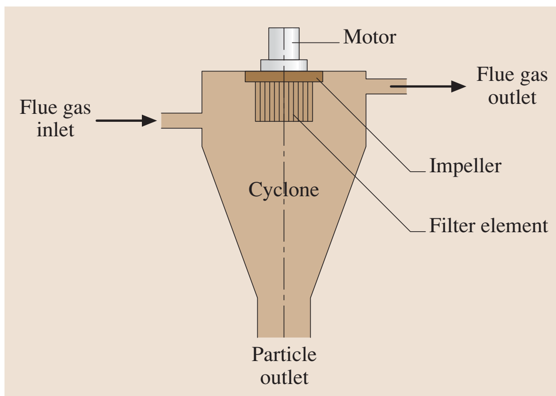

Fig. 16.36 Arrangement of a cyclone

The draft is the difference between the atmospheric pressure and the static pressure of the combustion gases in a furnace gas passage. In a coal-fired power plant tow methods are used to create a draught in the furnace:

1. A natural draft, or
2. A mechanical draft

16.22.7 Natural Draft

Natural draft establishes furnace breathing by continuous exhalation of flue gas and continuous inhalation of fresh air (Fig. 16.37). The tall chimney creates the natural draught by the temperature difference between the hot gases in the chimney and the cold atmospheric air outside the chimney.

The advantages of this method are:

- No external power is required.
- Air pollution is less since gases are discharged at a high level.
- No maintenance cost.
- Capital cost is less than artificial draught.

The draught or pressure difference produced is given by

$$\Delta p_{nd} = \pm(\rho_a - \rho_g) g H \,, \tag{16.60}$$

where Δp_{nd} is the head of natural draft (Pa), ρ_a is the ambient air density (kg/m^3), ρ_g is the gas density in the flue (kg/m^3), and H is the height difference between the beginning and the end of the section (m).

The flue gas density ρ_g is calculated as

$$\rho_g = \rho_g^0 \frac{273}{273 + T_g} \,, \tag{16.61}$$

where T_g is the gas temperature (°C), ρ_g is the gas density in the flue under standard atmospheric conditions (1 atm) kg/m^3

$$\rho_g^0 = \frac{1 - 0.01A + 1.302\alpha V^0}{V_g} \,, \tag{16.62}$$

where α^0 is the excess air ratio in the flue gas, V^0 is the theoretical air requirement for unit weight of fuel (N m^3/kg), V_g is flue gas produced per unit weight of fuel (N m^3/kg $\approx \alpha V^0$), and A is the percentage ash content of the fuel.

The stack provides two functions:

1. Assisting the fan in overcoming pressure losses
2. Helping disperse the gas effluent

The amount of flow is limited by the strength of the draft. The pressure variation inside the chimney differs from atmospheric pressure. The variation of chimney pressure depends on the temperature variation along the chimney, which itself depends on the rate of cooling of hot gas due to natural convection.

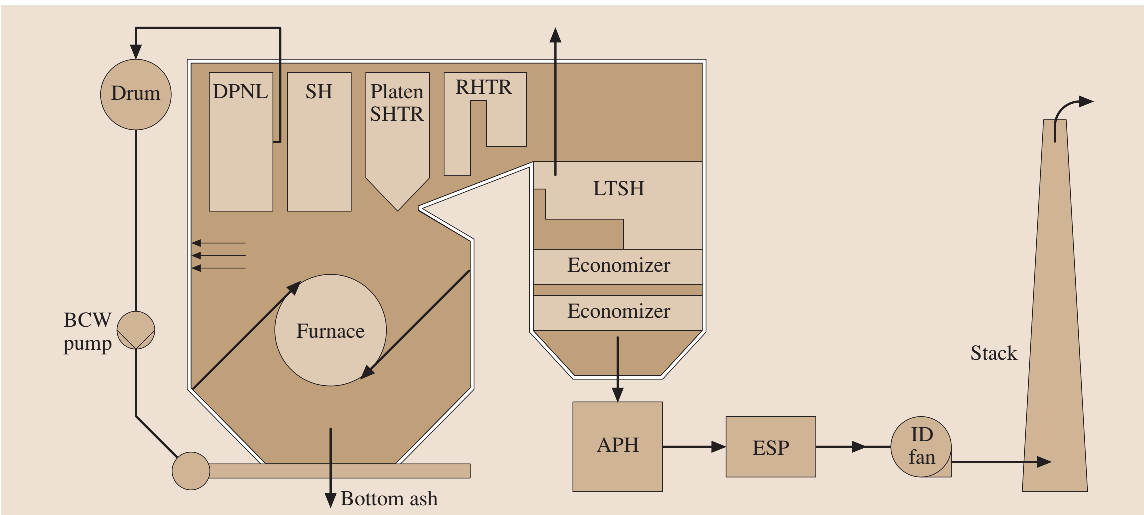

Fig. 16.37 Thermal structure of a boiler furnace (APH – air preheater, EPS – electrostatic precipitator, ID fan – induced draft fan, LTSH – latent superheater, platen SHTR – platen superheater, RHTR – reheater,SH – superheater)

16.22.8 Artificial Draught

In modern power plants, the draught should be flexible to meet the needs of fluctuating loads and it be independent of atmospheric conditions. To achieve this, the aid of draft fans becomes mandatory; by employing the fans, the height of the chimney can also be reduced. There are two types of fans used for producing mechanical draught:

1. Forced draught (FD)
2. Induced draught (ID)

16.22.9 Forced Draught

In this system, the blower (forced draft fan) is located at the base of the boiler near the grate. Air is forced into the furnace by the forced fan and the flue gases are forced to chimney through the economizer and air preheater.

Advantages of the Forced Draught System

- Since the fan handles cold air, the fan size and the power required are lower.
- No need for water-cooled bearings because the air being handled is cold.
- The pressure throughout the system is above atmospheric pressure so that air leakage into the furnace is reduced.

16.22.10 Induced Draught

In an induced draught system, a blower (induced draft fan) is placed near (or) at the base of the chimney. The fan sucks the flue gas from the furnace, creating a partial vacuum inside the furnace. Thus atmospheric air is induced to flow through the furnace to aid the combustion of fuel. The flue gases drawn by the fan passes through the chimney to the atmosphere.

16.22.11 Balanced Draught

In the induced draught system, when the furnace is opened for firing, cold air enters the furnace and dilates the combustion. In the forced draught system, when the furnace is opened for firing, the high-pressure air will try to blow out suddenly and the furnace may stop. Hence the furnace cannot be opened for firing and inspection in both systems. Balanced draught, which is a combination of induced and forced draught, is used to overcome these difficulties.

16.23 Environmental Control Technology

There are many technologies that can be used in industry to reduce the emissions of pollutants to the atmosphere, and these can be applied before, during, or after combustion.

16.23.1 Particulate Emission Control

There are several types of equipment available to control particulate matter from the flue gas which includes:

1. Electrostatic precipitators
2. Fabric filters
3. Mechanical collectors
4. Venturi scrubbers

16.23.2 Electrostatic Precipitators

When the ash particles present in the flue gas pass through the electrostatic precipitators (ESP) at a certain velocity, they become charged electrically and are attracted towards the collecting plate, which is normally positively charged.

Figure 16.35 shows a schematic diagram of ESP. The particulate-laden gas, normally laden with flyash, is sent through pipes with negatively charged plates which give the particles a negative charge. The particles are then routed past positively charged plates, or grounded plates, which attract the newly negatively charged ash particles. The particles stick to the positive plates until they are collected. The air that leaves the plates is then clean of harmful pollutants. Velocity is one of the important factors that affect the performance of an electrostatic precipitator. A lower velocity allows more time to collect the ash particles.

16.23.3 Fabric Filters

Fabric filters are used to remove particles from the gas stream. They are made up of woven or felted material. Fabric filters are generally in the form of a cylindrical bag. Fabric filters generally operate in a temperature range of 120–180 °C. The choice between ESP and fabric filtration generally depends on coal type, plant size, and boiler type and configuration. The two fundamen-

tal parameters in sizing and operating bag houses are the air-to-cloth (A/C) ratio (m/s) and the pressure drop (mm water gauge, Pascal or in H_2O). In operation, dust-laden gas flows through the filters, which remove the dust particles from the gas stream.

The most important factors that affect the performance of fabric filters are:

1. Flue gas temperature
2. Dew point and moisture content
3. Particle size distribution
4. Chemical composition of the fly ash

Fabric filters are classified into three types:

1. Pulse jet fabric filters
2. Reverse-air fabric filters
3. Shake-deflate filters

16.23.4 Pulse Jet Fabric Filters

Pulse jet fabric filters use high-pressure air to clean the filter bags, and are provided in standard configurations that are capable of treating gas flow rates up to about 300 000 ACFM (actual cubic feet per minute). Custom-designed units can handle larger flow rates.

16.23.5 Shake-Deflate Filters

This kind of filters collect the dust inside the bags as in the reverse-air design. To clean the bags, the top ends are shaken by a driver linkage.

16.23.6 Reverse-Air Fabric Filter

The reverse-air fabric filter is a customized design for utility boilers and industrial applications where large volumes of process gas flow (250 000 ACFM and more) must be cleaned. The systems consist of 6–24 structural compartments. Compartments are available with nominal 20 or 30 cm diameter bags with typical bag lengths of 7.31–11 m.

16.23.7 Mechanical Collectors

Mechanical dust collectors are often called cyclones. Cyclones are used to remove dust and fibrous material either as the first stage of a scrubber or fabric filter system. Although cyclones are an established form of dust collector, care and application knowledge are required to ensure correct sizing. The arrangement of a cyclone separator is shown in Fig. 16.36. The basic principle is the centrifugal force created by spinning a gas stream, which is used to separate the particles from the gas. In a conventional cyclone, the gas enters a cylinder tangentially, where it spins in a vortex as it proceeds down the cylinder. A cone section causes the vortex diameter to decrease until the gas reverses on itself and spins up the center to the outlet pipe or vortex finder. A cone causes flow reversal to occur sooner and makes the cyclone more compact. Dust particles are centrifuged toward the wall and collected by inertial impingement.

The collected dust flows down in the gas boundary layer to the cone apex where it is discharged through an airlock or into a dust hopper serving one or more parallel cyclone.

16.23.8 NO_x Control

It is very important to control the level of NO_x emitted from power plants. NO_2 from the exhaust reacts with sunlight and hydrocarbons to produce photochemical smog and acid rain constituents. The following techniques are used to reduce the level of NO_x formation in current practices:

- Low excess air operation
- Off-stoichiometric combustion, combustion modification
- Flue gas recirculation and treatment

Low Excess Air Operation

This technique involves a reduction in the total quantity of air used in the combustion process. By using less oxygen, the amount of NO_x produced is reduced.

Off-Stoichiometric Combustion

This technique involves the mixing of the fuel and air in a way that reduces the peak gas temperatures and peak oxygen concentrations. Advanced low-nitrogen-oxide burners can reduce emissions by up to 30%. Such burners can be installed in either new or existing combustion plants. For a low-NO_x burner, sudden heating up and temperature rise is important. In this case the high-temperature zone is very close to the burner compared with a conventional burner, so the pulverized coal is heated very rapidly in order to increase the fractional volatile and nitrogen release according to quantity introduced. Also, the recirculation flow near the center of the burner is important, because hot gas returning to the burner creates a very high-temperature region at this point. Altogether, the modified shape of the flow divider

and the pulverized fuel nozzle, together with an optimized strength of swirl in the air flow, produce a strong internal recirculation and NO_x reducing zone in the CI-a burner, with longer residence time in this region and reduced unburnt matter. So the result is a reduction of 50% in unburnt carbon and, at the same time, a significant reduction of at least 10% in NO_x production.

Over Fire Air (OFA)

This technique keeps the mixture fuel rich and completes the combustion process using air injection nozzles.

Combustion Modifications

Flue Gas Recirculation. A second method is to add some of the flue gas with the combustion air at the burner, normally known as flue gas recirculation. This increases the gas weight which must be heated by the chemical energy in the fuel, thereby reducing the flame temperature.

Flue Gas Treatment

Selective Noncatalytic Reduction Systems (SNCR). This technique involves the injection of ammonia (NH_3) or urea into the hot gas zone where reactions leading to reduction of nitrogen oxides can occur. The reactions are completed within the boiler, and no waste products are generated. There is a risk of ammonia (NH_3) being emitted into the atmosphere if temperatures are too low, however. SCNR systems are capable of reducing nitrogen oxides by 20–60%. The reactions are

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O\,,$$
$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O\,.$$

Flue Gas Desulphurization.
Precombustion Sulphur Control Technology. Removing the sulphur before burning is one of the challenging options. There are a verity of techniques available to reduce the sulphur, including coal scrubbing and oil desulphurization.

Another removal process is to change the design of the boiler and to install pressurized fluidized-bed combustors (FBC), which remove sulphur from the coal during the burning process.

Another process that removes sulphur dioxide from coal during combustion is the integrated gasification combined cycle. Coal is gasified under pressure with a mixture of air and steam which results in the formation of gas which can then be burned to produce electricity.

Post-Combustion Sulphur Control Technology. One of the post-combustion sulphur control methods (removing sulphur after burning) is flue gas desulphurization (FGD). In FGD processes, waste gases are scrubbed with a chemical absorbent such as limestone to remove sulphur dioxide. There are many different FGD processes, the main ones being the limestone–gypsum process and the Wellman–Lord regenerative process. Limestone–gypsum FGD involves mixing limestone and water with the flue gases to produce slurry which absorbs the sulphur dioxide. The slurry is then oxidized to calcium sulphate (gypsum) which can then be used in the building trade. FGD technologies can be classified into six main categories: wet scrubbers, spray dry scrubbers, sorbent injection processes, dry scrubbers, regenerable processes, and combined SO_2/NO_x removal processes.

16.24 Steam Generators

The steam generator is one of the main components in modern coal fired-power plants. Its concept, design, and integration into the overall plant considerably influence costs, operating behavior, and availability of the power plant. The thermal structure of the boiler furnace is shown in Fig. 16.37. Within the steam generator, fuel and air are forced into the furnace by the burner, where burning produces heat; from there fuel gas travels throughout the boiler, the feedwater absorbs the heat, and eventually absorbs enough energy to change into vapor. Boiler makers have developed various designs to extract the most energy from fuel and to maximize its transfer to the water.

Water enters the boiler, preheated, at the top as shown in the Fig. 16.37. The hot water naturally circulates through the tubes down to the lower area where it is hot. The water heats up and flows back to the steam drum, where the steam collects. Not all of the water is turned to steam, so the process starts again. Water keeps on circulating until it becomes steam. Meanwhile, the control system measures the temperature of the steam drum, along with numerous other readings, to determine if it should keep the burner burning, or shut it down. Sensors also control the amount of water entering the boiler, known as the feedwater. A steam generator is normally equipped with

basic component like a furnace, economizer, reheater, superheater, evaporator, air preheater, and auxiliary devices.

16.24.1 Types of Steam Generators

The classification of boilers depends on various phenomena, such as furnace position, the type of fuels used, tube contents, circulation etc.

16.24.2 Boiler Safety

Boiler safety is one of the prime aspects while operating the boiler. Operating the pressure above the design pressure is extremely dangerous, so proper control of the pressure inside the steam generator is very important. Though boilers are usually equipped with a pressure-relief valve, if the boiler fails to contain the expansion pressure, the steam energy is released instantly. This combination of exploding metal and superheated steam can be extremely dangerous.

The concentration of solids in the boiler should be measured and the boiler blow-down at such intervals as necessary to maintain established limits. Blow-down valves are placed at the lowest point of the boiler for the purpose of blowing sediment or scale from the boiler. They should be maintained in good working order and have to be opened and closed carefully when used.

Boilers should always be brought online slowly and cold water should never be injected into a hot system as sudden changes in temperature can warp or rupture the boiler. Because many boilers are fired by natural gas, diesel or fuel oil, special precautions need to be taken. Boiler operators should ensure that the fuel system, including valves, lines, and tanks, is operating properly with no leaks. The low-water cutoff is the most important electrical/mechanical device on a boiler for maintaining a safe water level. If a low-water condition develops, it could very well result in an overheating and explosion of the boiler. The low-water cutoff should be tested at least weekly.

To prevent furnace explosions, it is imperative that boiler operators purge the boiler before ignition of the burner. Workers should check the fuel-to-air ratio, the condition of the draft, and the flame to make sure that it is not too high and not smoky. Ventilation systems should also be inspected and maintained to make sure that combustion gases do not build up in the boiler room.

16.24.3 Boiler Water Treatment

Efficient performance of the boiler depends upon the quality of the water. The treatment of the boiler feedwater is required to prevent excessive fouling of the heat transfer equipment and the erosion of turbine blades.

The common impurities present in the raw water are:

1. Dissolved solids – calcium, magnesium
2. Suspended solids – mineral matter
3. Dissolved gases – oxygen and carbon dioxide
4. Scum-forming substances – carbonate, chlorate, and sulphate

In the steam boiler industry, high-purity feedwater is required to ensure proper operation of steam generation systems. High-purity feedwater reduces the use of boiler chemicals due to less frequent blow-down requirements. This lower blow-down frequency also results in lower fuel costs.

The boiler system loses water through steam and water leaks. Additional water called *make-up water* is added to the boiler to replace these losses. The amount of make-up water and the level of naturally occurring impurities in this water will determine the type of water treatment required. Boiler heating systems that have very few leaks require a simple water treatment program.

All water contains dissolved minerals and these minerals, if allowed to reach high enough levels in the boiler water, will come out of solutions and form as a hard shell on the hot surfaces of the boiler. This hard shell is called *scale* and is often found on the outside of the fire tubes or the inside of water tubes. Scale insulates the heating surfaces, reducing the ability of the fire tubes to transfer heat from the hot combustion to the boiler water. High stack temperatures or ruptured tubes are common problems related to scale build up. Boiler water also contains dissolved gases such as oxygen or carbon dioxide. These gases, in the presence of water and metal, can cause corrosion. Corrosion eats away the metal, affecting the durability of the boiler.

For boiler feedwater treatment, depending on its requirements, a number of processes can be utilized including chemical treatment/lime softening, dual-media filtration, carbon adsorption, conventional reverse osmosis membranes, and final ion-exchange resin polishing. Various methods of pretreatment of water are discussed below.

Lime Soda Process

Calcium and magnesium salts are removed using lime and soda ash. The chemical reactions during this process are

$$\begin{aligned} Ca(HCO_3)_2 + Ca(OH)_2 &= 2CaCO_3 + 2H_2O\,, \\ MgCl_2 + Ca(OH)_2 &= Mg(OH)_2 + CaCl_2\,, \\ MgSO_4 + Ca(OH)_2 &= Mg(OH)_2 + CaSO_4\,, \\ CaSO_4 + Na_2CO_3 &= CaCO_3 + Na_2SO_4\,, \\ CaCl_2 + Na_2CO_3 &= CaCO_3 + 2NaCl\,. \end{aligned}$$

Insoluble components such as calcium carbonate and magnesium hydroxide settle at the bottom.

Deaeration

The feedwater from the condenser contains dissolved gases such as O_2 and CO_2. Oxygen is found in feedwater with a relatively high partial pressure, so, it requires a near saturation temperature to be disassociated from the water. Oxygen in combination with water will attack iron and cause corrosion. This reaction occurs in two steps

$$Fe^{2+} + 2OH^- = Fe(OH)_2\,.$$

Then,

$$\begin{array}{ccccccc} 4Fe(OH)_2 & + & O_2 & + & 2H_2O & = & 4Fe(OH)_3 \\ \text{Soluble} & & \text{Dissolved} & & \text{Water} & & \text{Insoluble} \\ \text{ferrous} & & \text{oxygen} & & & & \text{ferric} \\ \text{hydroxide} & & & & & & \text{hydroxide} \end{array}$$

A deaerator is an open-type feedwater heater, in which the steam that is bled from the turbine is mixed directly with water. When the water temperature increases, the dissolved gases reduce.

16.24.4 Shell-Type Steam Generator

This is a cylindrical boiler where the shell axis is vertical to the firing floor. Originally it consisted of a chamber at the lower end of the shell, which contained the combustion appliance. The gases rose vertically through a flue surrounded by water. Large-diameter (100 mm) cross tubes were fitted across this flue to help extract heat from the gases, which then proceeded to the chimney. Later versions had the vertical flue replaced by one or two banks of small-bore tubes running horizontally before the gases discharged to the chimney. The steam was contained in a hemispherical chamber forming the top of the shell.

The present vertical boiler is generally used for heat recovery from exhaust gases from power generation or marine applications. The gases pass through small-bore vertical tube banks. The same shell may also contain an independently fired section to produce steam at such times that there is insufficient or no exhaust gas available.

In relation to the thermal capacity generated, a shell-type boiler has much higher water contents than a water tube boiler. Therefore, a shell-type boiler is more robust towards load fluctuations or load demands that temporarily exceed the rated boiler capacity.

Shell-type boilers are fire-tube boilers, because the products of combustion pass through the boiler tubes. Lancashire and Cornish are examples of shell-type boilers.

16.24.5 Natural Circulation Boiler

The distinct features of natural circulation boiler are that natural circulation occurs due to the density difference between the fluids in the down comer and riser or is caused by convection currents that result from the uneven heating of the water contained in the boiler. The natural circulation has been largely used in boilers up to 140 bar. Based upon the position and geometry natural circulation boilers are classified into two types:

1. Vertical-tube type
2. Sloped-tube type

Figure 16.39 shows a typical water-tube natural circulation waste heat boiler with steam drum and down comer and riser pipes. Feedwater enters the drum from an economizer. This mixes with the steam/water mixture inside the drum. Down comers carry the resultant cool water to the bottom of the evaporator tubes while external risers carry the water–steam mixture to the steam drum. The heat transfer tubes also act as risers, generating steam.

The natural circulation is maintained due to the static head difference and natural convection due to the density differential between the mean down comer density and mean riser density. The down comers are located outside the furnace and away from the heat of combustion. They serve as pathways for the downward flow of relatively cool water.

The circulation ratio is defined as the ratio of the mass of steam–water mixture to steam generation. The natural circulation largely depends upon the

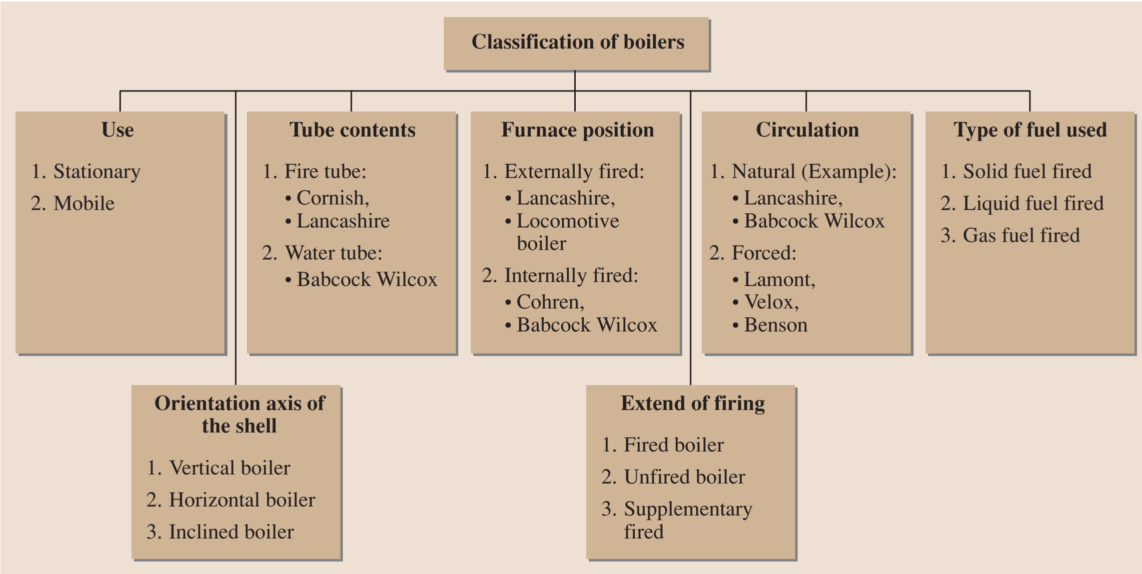

Fig. 16.38 Classification of boilers

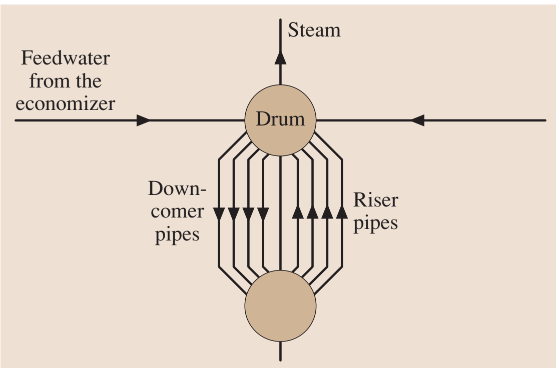

Fig. 16.39 Natural-circulation-type water tube boiler

height of the riser and the down comer, and the mean density of the fluids. The main feature of natural circulation boilers is the absence of water circulation pumps.

16.24.6 Forced Circulation Boiler

Modern boilers use the principle of forced circulation. When the boiler pressure is very high, the difference between the densities of water and the saturated steam decreases and hence less circulation occurs. The difference between the lower drum and steam drum must be increased in order to obtain the same output under higher-pressure condition. This can be achieved by means of forced circulation. The example of a forced circulation boiler is the Lamont boiler. The operation is basically similar to that of natural circulation unit, with a pump being used below the down comer for circulating water through the risers.

Normally forced circulation boilers are used if the pressure is very high. If the pressure is very high, the density difference between liquid/water and liquid mixture is very less, so, there abstract the problem of free flow like in natural circulation.

A once-through boiler is a forced circulation boiler. Once-through boilers have been favored in many countries for more than 30 years. They can be used up to a pressure of more than 30 MPa without any change in the process engineering. In the once-through boiler, subcooled water, supplied by a feedwater pump at the inlet of the tubes, is heated, evaporated, and superheated in the long evaporation tubes to produce superheated steam at a prescribed pressure and temperature at the outlet of the tubes.

A principle advantage of the once-through boiler is that it does not require circulating pumps or drums. The energy required for circulation is provided by the feed pump. Since the state of the superheated steam at the outlet is determined by the total amount of heat input, independent of the heat the heat flux distribution along the tube at a defined mass flow rate, the once-through boiler is a fairly simple device to obtain superheated steam of a prescribed state at any partial load.

16.24.7 Boiling Water Reactors

The fission zone is contained in a reactor pressure vessel, at a pressure of about 70 bar (7 MPa). At the temperature reached (approximately 290 °C), the water starts to boil and the resulting steam is produced directly in the reactor pressure vessel. After the separation of the steam and water in the upper part of the reactor pressure vessel, the steam is routed directly to a turbine driving an alternator. The steam coming out of the turbine is converted back into water by a condenser after having delivered a large amount of its energy to the turbine. It is then fed back into the primary cooling circuit where it absorbs new heat in the fission zone. Since the steam produced in the fission zone is slightly radioactive, mainly due to short-lived activation products, the turbine is housed in the same reinforced building as the reactor.

16.25 Parts and Components of Steam Generator

16.25.1 Superheaters

One of the most important accessories of a boiler is a superheater, which affects improvement and economy in the following ways. The steam that is produced in the boiler has a certain percentage moisture content. Due to the high velocities of the steam inside a turbine, the moisture content of the steam can erode the turbine blades. A superheater is utilized to remove the moisture content in the steam by raising the temperature while keeping the pressure constant. Steam that undergoes this process is referred to as superheated steam. Superheating improves the turbine internal efficiency and hence the lifetime of the turbine. The degree of superheating is a term which is used to describe the temperature difference between the raised temperature and the temperature at constant pressure.

A superheater therefore:

1. Increases the capacity of the plant
2. Reduces corrosion of the steam turbine
3. Reduces steam consumption of the steam turbine

Depending upon the way heat is transferred, superheaters are classified into three types:

1. Radiant superheaters
2. Convective superheaters
3. Combined radiative and convective superheaters

Convective superheaters are normally called primary superheaters and are located near the convective zone of the furnace, whereas radiant and combined superheaters are termed secondary superheaters.

Flow Arrangements of the Different Types of Superheater

The saturated steam from the drum is sent into the convective superheaters. After the convective superheater the steam is passed into the radiant superheater, where the heat is absorbed purely by means of radiation. Steam leaving the radiant superheater is sent into the desuperheater, where highly pure water is sprayed directly into the steam. The temperature of the steam leaving the pendent superheater should not exceed the rated value.

Superheaters are often divided into more than one stage such as:

1. A platen superheater
2. A pendent superheater
3. A horizontal superheater
4. A radiant superheaters

16.25.2 Radiant Superheater

Radiant superheaters receive energy primarily by thermal radiation from the furnace with little energy from convective heat transfer. Radiant superheaters are located at the furnace exit or turning section. The radiant superheater absorbs more enthalpy at partial loads when compared to the convective type. At lower loads the flow distribution inside the superheater tubes is less uniform. The radiant superheater outlet temperature decreases with increasing boiler output. At higher loads the mass flow rate of the combustion gas is high, because of increased amount of fuel and air for combustion. The convective heat transfer coefficient increases both inside and outside the tubes. Thus the steam receives more heat transfer per unit mass flow rate, and its temperature increases with load. The surface area required to transfer a given amount of energy will be lower due to the higher log mean temperature difference and higher heat transfer coefficient. Hence their cost may be lower in spite of the better grade of materials required.

16.25.3 Convective Heat Transfer

A convective superheater is located in a low-gas-temperature region ranging from 423 to 813 K lower, depending on the degree of superheating required. Since it is shielded by several rows of screen tubes, the gas is well mixed and cooled before it encounters the superheater and hence the performance can be predicted more accurately. Due to the Lower log mean temperature difference and lower heat transfer coefficient, the surface area required will be greater and the device hence could therefore be more expensive than the radiant design.

16.25.4 Pendent Superheater

Pendent superheaters receive heat by both convection and radiation, they are normally hung from the top as shown in the Fig. 16.40, usually located in the crossover duct between the furnace and the back pass.

The outside tube diameters of the pendent superheaters normally falls in the range 32–51 mm and the tube thickness is usually in the range 3–7 mm.

16.25.5 Platen Superheater

These devices are made from flat panels of tubes located in the upper part of the furnace, where the gas temperature is high. The tubes of the platen superheater receive very high radiation as well as a heavy dust burden, so ultimate care should be taken while designing platen superheaters. The arrangement of platen superheater is shown in Fig. 16.41.

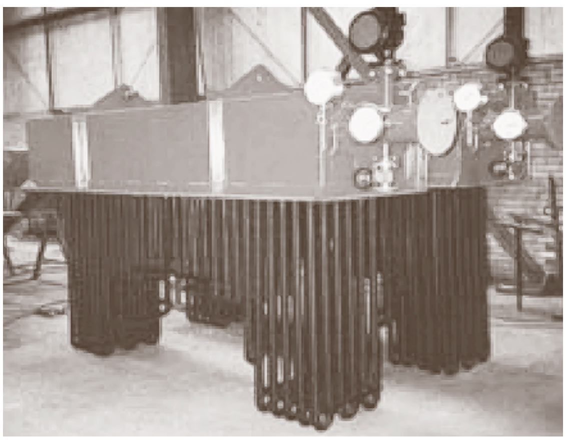

Fig. 16.40 Arrangement of a pendent superheater

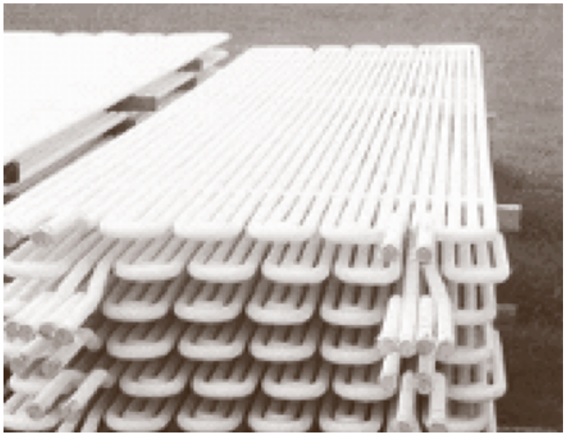

Fig. 16.41 Arrangement of a platen superheater

The mass flow velocity of steam in the platen superheater is normally in the range 800–1000 kg/(m^2 s). The outer diameter of the platen superheater tubes is in the range 32–42 mm. The number of parallel tubes in a platen is generally 15–35, depending on the design steam velocity.

16.25.6 Reheaters

The design considerations for reheaters are similar to those for superheaters. The reheater is usually located above the primary or convective superheater in the convective zone of utility boilers. A schematic view of a convective reheater is shown in Fig. 16.43. The pressure drop inside the reheater tubes has an important adverse effect on the efficiency of the turbine. The pressure drop through the reheater should be kept as low as possible. The tube diameter of the reheater is normally 42–60 mm and the overall heat transfer coefficient is 90–110 W/(m^2 K).

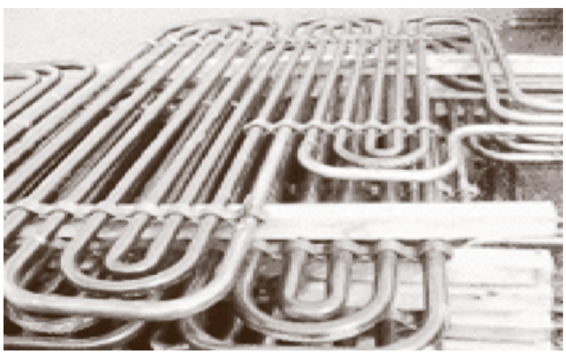

Fig. 16.42 Schematic view of convective reheaters

16.25.7 Economizers

The feedwater from the first high-pressure heater passing through a heat exchanger and heats up to the saturation temperature corresponding to the boiler pressure. This heat exchanger is normally called the economizer; it extracts waste heat from hot stack gases to heat the feedwater to the desired saturation temperature, hence the energy input to the boiler increases and the efficiency as well as economy of the power plant increase. The economizer is generally placed between the convective superheater and the air preheater.

Economizers are designed for downward flow of gas and upward flow of water, consisting of more than 250–300 coils in a staggered arrangement in a single bank. Figure 16.43 depicts the arrangement of the economizer.

Water enters from a lower header and flows through horizontal tubes that comprise the heating surface. Return bends at the ends of the tubing provide continuous tube elements whose upper ends connect to the outlet headers, which are in turn connected to the boiler drum by means of piping. Modern power plants use steel-tube-type economizers. The outside diameter of the economizer tubes is normally in the range 25–75 mm and the tube thickness is 3–5 mm; providing an extended surface over the economizer will enhance the heat transfer rate.

16.25.8 Feedwater Heaters

Feedwater heaters are used to raise the temperature of the water or to increase the mean temperature of heat addition in the cycle before it enters the boiler. The feedwater heater utilizes the steam which is extracted along the turbine expansion line for water heating. Feedwater heaters are used in a regenerative feedwater cycle to increase thermal efficiency and thus provide fuel savings.

Feedwater heaters are normally classified into two types

1. Open feedwater heaters
2. Closed feedwater heaters

Closed Feedwater Heaters

A closed feedwater heater is a shell-and-tube heat exchanger that warms feedwater by means of superheated steam or dry saturated or wet steam. Normally water flows inside the pipe and steam flows on the shell side. The arrangement of a closed feedwater heater in a typical steam turbine power plant is shown in Fig. 16.44.

According to the method of releasing the drain, closed feedwater arrangements are further classified into two types:

1. Drain cascaded forward
2. Drain cascaded backward

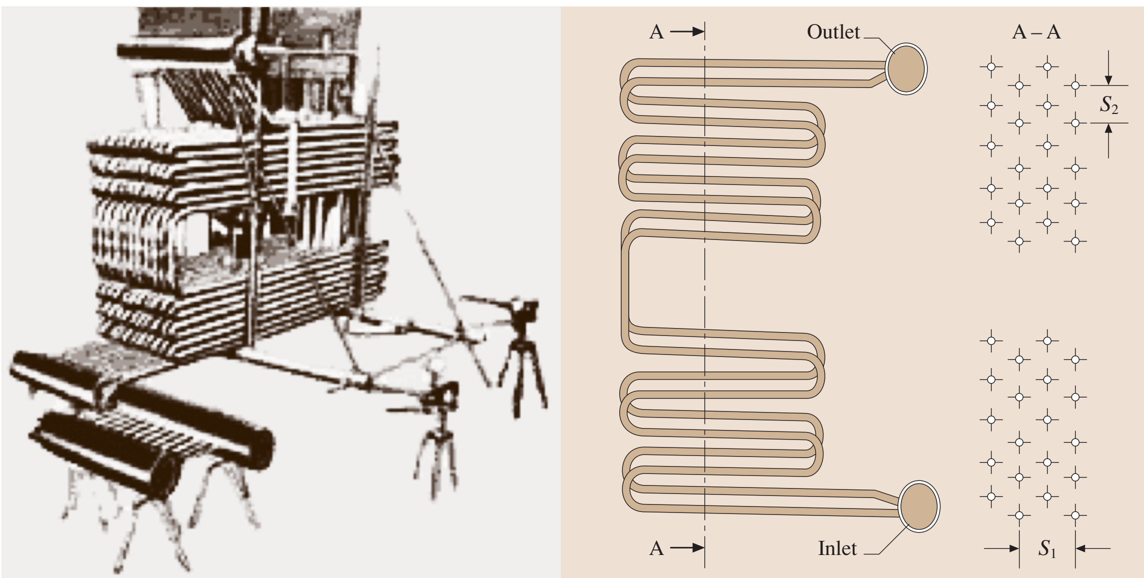

Fig. 16.43 Arrangement of an economizer

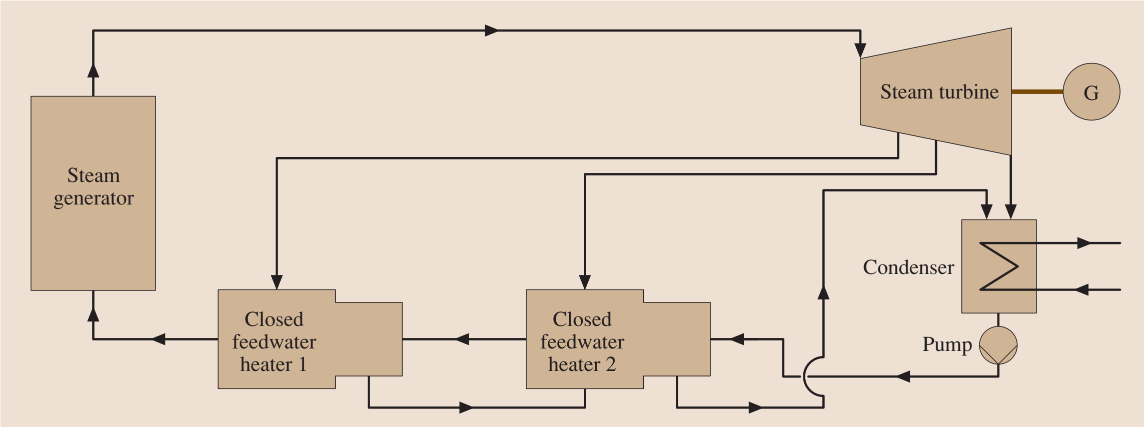

Fig. 16.44 Steam turbine regenerative cycle with closed feedwater heater (drains cascaded backward)

In the drain cascaded forward type the drain from the feedwater heater is mixed with the drain from the preceding feedwater heater. The reverse happens in the drain cascaded backward type, as shown in Fig. 16.44. Based on the state of the steam or level of turbine extraction feedwater heaters are further classified as high-, intermediate-, and low-pressure feedwater heaters. Modern power plants employing regeneration normally employ more than six feedwater heaters. There should always be one deaerator along with open feedwater heater. The purpose of the deaerator is to remove the dissolved oxygen presence in the system. High-pressure (HP) feedwater heaters utilize steam from the HP turbine and hence are called high-pressure feedwater heaters. A high-pressure closed feedwater heater has three zones, namely the desuperheating zone, the condensing zone, and the drain cooling zone. During the design of such a heat exchanger each zone is consider as a separate heat exchanger and the corresponding heat transfer coefficients and pressure drops are evaluated separately. The temperature duty diagram for a three-zone feedwater heater or high-pressure closed feedwater heater is shown in Fig. 16.45.

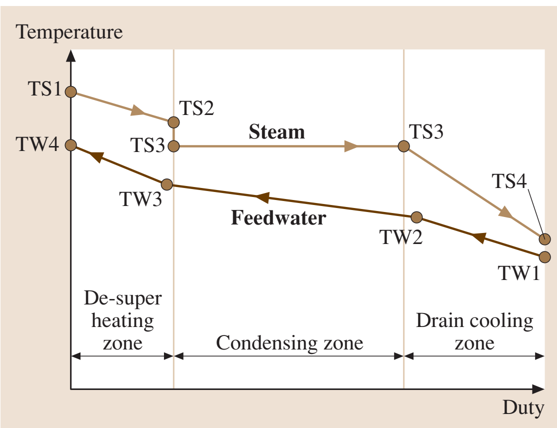

Fig. 16.45 Temperature–duty diagram for a three-zone feedwater heater

Open Feedwater Heaters

In open feedwater heaters, heat transfer takes place by direct mixing of steam and water. Normally open feedwater heaters are more efficient than closed feedwater heaters. Though the efficiency of open feedwater heater is higher, closed feedwater is normally used for modern power plants utilizing a large number of feedwater heaters to avoid a large number of pumps at each entrance and exit of the heater.

16.25.9 Air Preheaters

The flue gas leaving the chimney is normally in the range 280–480 °C. Leaving the flue to the atmosphere at this high temperature causes high energy losses. Air heaters are used to utilize this hot flue gas to heat the air required for combustion, and lead to an improvement in combustion efficiency. Since this is a gas-to-gas heat exchanger, its heat transfer surface area is extremely large. Recuperative and regenerative heaters are two different air preheaters normally employed in power plants.

16.25.10 Recuperative Air Preheater

A recuperative air preheater is nothing but a shell-and-tube heat exchanger in which hot flue gas flows inside

the tubes and air flows outside. Since this is a gas-to-gas heat exchanger it requires a huge heat transfer surface area and hence larger size.

16.25.11 Rotary or Regenerative Air Preheater

Rotary preheaters works on the counterflow principle, and consist of a rotor and housing. The rotor is normally divided into 12–24 radial divisions of heat transfer elements and is made up of steel sheets. The rotor is driven by an electric motor and is coupled with worm-gear drive that helps to reduce the speed of the rotor device to 2–6 rpm. During the rotation through the flue gas side the heat transfer element absorbs heat which is later given off during the rotation through the air section. Based on the number of sections rotary preheaters are further classified into three types: bisector, trisector, and quadsector types. Trisector-type air preheaters are divided into three sections: one for the flue gas, one for the primary, and one for the secondary section. In the quadsector type, the secondary air section is divided into two sections, taking up primary air. Control of the leakage of air into the flue gases is very important to avoid energy loss in the system. Various types of sealing systems are normally employed:

1. Radial sealing system
2. Axial sealing system
3. Circumferential sealing system
4. Shaft sealing system

16.26 Energy Balance Analysis of a Furnace/Combustion System

16.26.1 Performance Analysis of a Furnace

The following procedures should be adopted to carry out the performance analysis of the furnace:

1. Obtain the ultimate fuel analysis
2. Compute the equivalent chemical formula
3. Select the recommended exhaust gas composition
4. Write and balance the combustion equation

$$\begin{aligned} &\mathrm{C}_X\mathrm{H}_Y\mathrm{S}_Z\mathrm{O}_K + \varepsilon 4.76\left(X + \frac{Y}{4} + Z - \frac{K}{2}\right)\ \text{air} \\ &\quad + \text{moisture in air} + \text{ash moisture in fuel} \\ &\to P\mathrm{CO}_2 + Q\mathrm{H}_2\mathrm{O} + R\mathrm{SO}_2 + T\mathrm{N}_2 + U\mathrm{O}_2 \\ &\quad + V\mathrm{CO} + W\mathrm{C} + \text{ash}\ . \end{aligned}$$

Dry Exhaust Gases.

$$P\mathrm{CO}_2 + R\mathrm{SO}_2 + T\mathrm{N}_2 + U\mathrm{O}_2 + V\mathrm{CO} \quad (\text{kmol})\ .$$

1. Carry out first law analysis to calculate the theoretical combustion temperature.
2. Calculate the total number of moles of wet exhaust gas for 100 kg of fuel
$$n_{\text{ex.gas}} = P + Q + R + T + U + V\ .$$
3. 100 CV of fuel $= n_{\text{ex.gas}} c_{\text{pexhaust gas}} (T_{\text{th}} - T_{\text{atm}})$.
4. Calculate the total heat transfer area of the furnace A_{furnace}.

16.26.2 Analysis

$$\begin{aligned} &\mathrm{C}_X\mathrm{H}_Y\mathrm{S}_Z\mathrm{O}_K + \varepsilon 4.76\left(X + \frac{Y}{4} + Z - \frac{K}{2}\right)\ \text{air} \\ &\quad + \text{moisture in air} + \text{ash moisture in fuel} \\ &\to P\mathrm{CO}_2 + Q\mathrm{H}_2\mathrm{O} + R\mathrm{SO}_2 + T\mathrm{N}_2 + U\mathrm{O}_2 \\ &\quad + V\mathrm{CO} + W\mathrm{C} + \text{ash}\ . \end{aligned}$$

Dry exhaust gases

$$P\mathrm{CO}_2 + R\mathrm{SO}_2 + T\mathrm{N}_2 + U\mathrm{O}_2 + V\mathrm{CO} \quad (\text{kmol})\ .$$

The volume of gases is directly proportional to the number of moles

Volume fraction = mole fraction

Volume fraction of CO_2

$$x_1 = P\frac{100}{(P + R + T + U + V)}\ .$$

Volume fraction of CO

$$x_2 = V\mathrm{CO}\frac{100}{(P + R + T + U + V)}\ .$$

Volume fraction of SO_2

$$x_3 = R\frac{100}{(P + R + T + U + V)}\ .$$

Volume fraction of O_2

$$x_4 = U\frac{100}{(P+R+T+U+V)} .$$

Volume fraction of N_2

$$x_5 = T\frac{100}{(P+R+T+U+V)} .$$

These are dry gas volume fractions. Emission measurement devices only indicate dry gas volume fractions.

Measurements

Volume flow rate of air, volume flow rate of exhaust are obtained from exhaust gas analysis

$$x_1 + x_2 + x_3 + x_4 + x_5 = 100 \text{ or } 1 .$$

Ultimate Analysis of Coal

$$\begin{aligned} &n\mathrm{C}_X\mathrm{H}_Y\mathrm{S}_Z\mathrm{O}_K + \varepsilon n 4.76\left(X + \frac{Y}{4} + Z - \frac{K}{2}\right) \text{ air} \\ &\quad + \text{moisture in air} + \text{ash and moisture in fuel} \\ &\to x_1\mathrm{CO}_2 + x_6\mathrm{H}_2\mathrm{O} + x_3\mathrm{SO}_2 + x_5\mathrm{N}_2 + x_4\mathrm{O}_2 \\ &\quad + x_2\mathrm{CO} + x_7\mathrm{C} + \text{ash} , \end{aligned}$$

where x_1, x_2, x_3, x_4, and x_5 are dry volume fractions or percentages.

Conservation Species. Conservation of carbon

$$nX = x_1 + x_2 + x_7 .$$

Conservation of hydrogen

$$nY = 2x_6 .$$

Conservation of oxygen

$$\begin{aligned} &nK + 2n\varepsilon\left(X + \frac{Y}{4} + Z - \frac{K}{2}\right) \\ &= 2x_1 + x_2 + 2x_3 + 2x_4 + x_6 . \end{aligned}$$

Conservation of nitrogen

$$\varepsilon n 3.76\left(X + \frac{Y}{4} + Z - \frac{K}{2}\right) = x_5 .$$

Conservation of sulfur

$$nZ = x_3 .$$

By rearranging the terms, we obtain

$$\begin{aligned} &\mathrm{C}_X\mathrm{H}_Y\mathrm{S}_Z\mathrm{O}_K + \varepsilon 4.76\left(X + \frac{Y}{4} + Z - \frac{K}{2}\right) \text{ air} \\ &\quad + \text{moisture in air} + \text{ash moisture in fuel} \\ &\to P\mathrm{CO}_2 + Q\mathrm{H}_2\mathrm{O} + R\mathrm{SO}_2 + T\mathrm{N}_2 + U\mathrm{O}_2 \\ &\quad + V\mathrm{CO} + W\mathrm{C} + \text{ash} . \end{aligned}$$

16.26.3 First Law Analysis of Combustion

$$\begin{aligned} &\mathrm{C}_X\mathrm{H}_Y\mathrm{S}_Z\mathrm{O}_K + \varepsilon 4.76\left(X + \frac{Y}{4} + Z - \frac{K}{2}\right) \text{ air} \\ &\quad + \text{moisture in air} + \text{ash} + \text{moisture in fuel} \\ &\to P\mathrm{CO}_2 + Q\mathrm{H}_2\mathrm{O} + R\mathrm{SO}_2 + T\mathrm{N}_2 + U\mathrm{O}_2 \\ &\quad + V\mathrm{CO} + W\mathrm{C} + \text{ash} , \end{aligned}$$

$$\begin{aligned} &\sum Q_{\mathrm{CV}} + n_{\mathrm{air}}h_{\mathrm{f,air}} + n_{\mathrm{fuel}}h_{\mathrm{f,fuel}} \\ &= \sum_{i=1}^{n} n_i h_{\mathrm{f,fluegas},i} + \sum W_{\mathrm{CV}} . \end{aligned} \tag{16.63}$$

Furnace characterization criteria

$$A_{\mathrm{furnace}} = \frac{Gm_{\mathrm{f}}c_{\mathrm{P}}}{T_{\mathrm{th}}^3}\left[\frac{1}{m}\left(\frac{T_{\mathrm{th}}}{T_{\mathrm{out}}} - 1\right)\right]^{1/0.6} , \tag{16.64}$$

where G is the furnace quality factor, M is the temperature field coefficient, T_{th} is the theoretical combustion temperature, A_{furnace} is the total surface area of the furnace, and m_{f} is the mass flow rate of fuel.

16.26.4 Boiler Fuel Consumption and Efficiency Calculation

For any fuel there is a minimum quantity of oxygen required for complete combustion. The amount of air that contains this minimum quantity of oxygen is called the *theoretical air*; it is the measure of capability of the boiler to transfer heat liberated in the furnace to water and steam. The boiler efficiency may be expressed in any one of the following methods.

16.26.5 Various Energy Losses in a Steam Generator

1. Heat loss from the furnace surface area
2. Unburned carbon loss
3. Incomplete combustion loss
4. Loss due to hot ash
5. Loss due to moisture in the air
6. Loss due to moisture in the fuel
7. Loss due to combustion-generated moisture
8. Dry exhaust gas losses

The pictorial representation of the Shanky diagram, as shown in Fig. 16.47, represents the various energy losses that take place in a steam generator.

The first law analysis steam generator in steady state steady flow (SSSF) mode in molar form (see Fig. 16.48)

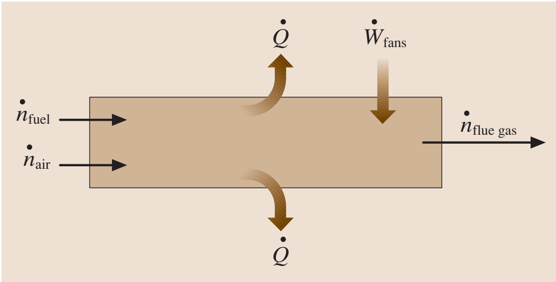

Fig. 16.46 Energy balance diagram

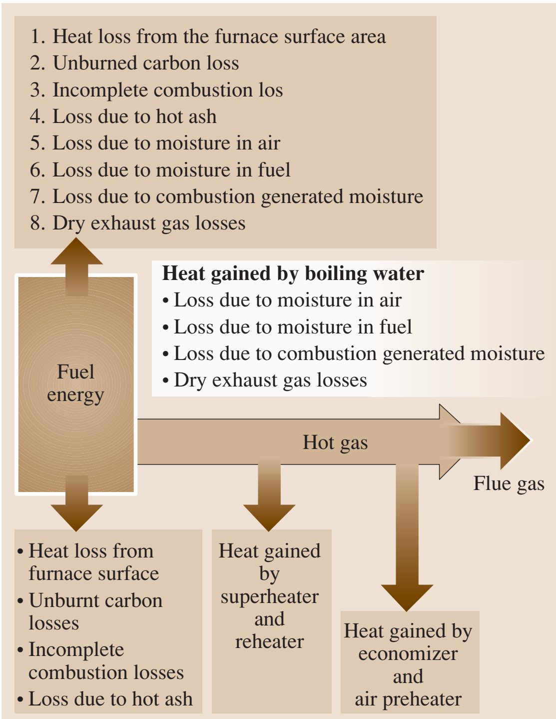

Fig. 16.47 Shanky diagram showing various losses in the steam generator

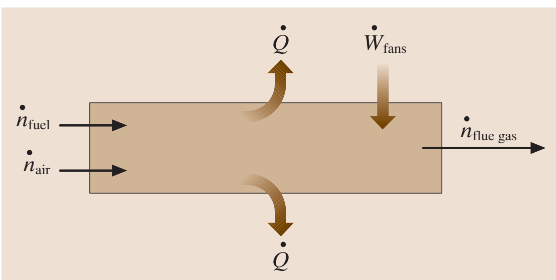

Fig. 16.48 Furnace energy balance

yields

$$\sum \dot{Q} + \dot{n}_{air} h_{air} + \dot{n}_{fuel} h_{fuel} = \sum \dot{n}_{fluegas} h_{fluegas} + \sum \dot{w}\ .$$

Dry Exhaust Gas Losses (DEGL)

For 100 kg of fuel

$$Q_{DEGL} = \Delta n_{fluegas} \Delta h_{fluegas}\ ,$$
$$Q_{DEGL} = n_{CO_2} \Delta h_{CO_2} + n_{CO} \Delta h_{CO} + n_{O_2} \Delta h_{O_2} + n_{N_2} \Delta h_{N_2} + n_{SO_2} \Delta h_{SO_2}\ \text{kJ}\ ,$$
$$Q_{DEGL} = P \Delta h_{CO_2} + R \Delta h_{SO_2} + T \Delta h_{N_2} + U \Delta h_{O_2} + v \Delta h_{CO}\ \text{kJ}\ .$$

Alternate method. The total number of moles of dry exhaust gas $n_{ex.gas} = P + R + T + U + V$ is

$$Q_{DEGL} = n_{ex.gas} C_{p,ex.gas} (T_{ex.gas} - T_{atm})\ .$$

Accurate calculation of the gas enthalpy gives, for any gas

$$\mathrm{d}h = c_p\,\mathrm{d}T\ ,$$
$$\Delta h = \int_{ambient}^{SG_{exit}} \mathrm{d}h = \int_{T_{amb}}^{T_{exit}} c_p(T)\,\mathrm{d}T\ . \tag{16.65}$$

Unburnt Carbon Loss (UCL)

For 100 kg of fuel

$$Q_{UCL} = \text{MC}\ W\ \text{calorific value of carbon} \quad (\text{kJ})\ ,$$
$$Q_{UCL} = 12W\ 33\,820\ \text{kJ}\ , \tag{16.66}$$

where MC is the molecular weight of carbon.

Incomplete Combustion Loss (ICL)

For 100 kg of fuel

$$Q_{ICL} = \text{MCO}VCV\ \text{of CO} \quad (\text{kJ})\ ,$$
$$Q_{ICL} = 28V\ 23\,717\ \text{kJ}\ . \tag{16.67}$$

Losses due to Moisture in the Combustion Air (MCAL)

$$Q_{MCAL} = e4.76\left(X + \frac{Y}{2} + Z - \frac{K}{2}\right) \times 29.9 w c_{steam} (T_g - 25) \quad (\text{kJ})\ , \tag{16.68}$$

where w is the absolute or specific humidity (kg of moisture per kg of dry air), c_{steam} is the specific heat

of steam at constant pressure ($1.88\,\mathrm{kJ/(kg\,K)}$), and T_g is the temperature of exhaust gas.

Losses due to Moisture in Fuel and Combustion Generated Moisture

For 100 kg of fuel

$$Q_{ML} = (M + 9Y)[2442 + c_{steam}(T_g - 25)] \quad (\mathrm{kJ})\,, \tag{16.69}$$

where M is the percentage moisture content in the fuel and Y is the combustible hydrogen atoms in the fuel.

Losses due to Hot Ash or Slag (ASL)

For 100 kg of fuel

$$Q_{ASL} = Ac_{p,as}T_{ash}\,, \tag{16.70}$$

where $c_{p,ash}$ is the specific heat of ash (0.55–$0.6\,\mathrm{kJ/(kg,K)}$), T_{ash} is the temperature of the ash or slag, and T_{ash} varies from 300 to 800 °C.

Radiation and Unaccounted-for Losses (RUL)

This calculation captures losses due to radiation and incomplete combustion resulting in hydrogen and hydrocarbons in the flue gases. While the radiation and unaccounted loss is relatively small, it is difficult to determine accurately. In practice, this loss is 3–5%.

$$Q_{RCL} = A_s(h_s)(T_{surface} - T_{amb}) \quad (\mathrm{kW})\,, \tag{16.71}$$

where A_s is the total surface area (m^2), and h_s is the surface heat transfer coefficient.

16.27 Performance of Steam Generator

16.27.1 Boiler Efficiency

This is the measure of the capability of the boiler to transfer heat liberated in the furnace into water and steam. The boiler efficiency may be expressed in any of the following methods

$$\eta_{boiler} = \frac{\text{mass flow rate of steam} \times (\text{steam heat} - \text{feedwater heat})}{\text{fuel mass} \times \text{heating value of fuel}}$$

or

$$\eta_{boiler} = \frac{(\mathrm{HHV} - \text{total loss})}{\mathrm{HHV}}\,, \tag{16.72}$$

where HHV is the higher heating value of the fuel.

16.28 Furnace Design

There are two aspects of furnace design. The first is concerned with the generation of the heat; the second part involves the absorption of the heat in the furnace. The amount of fuel can be burned in the given furnace volume, liberating the required amount of heat.

The heat release rate and furnace gas temperature are two of the important parameters used for the design of the size of the furnace. The heat release rate is expressed on three different bases: furnace volume (q_v), furnace cross-sectional area, and water wall area in the burner region (q_b).

The important thermal characteristic of the furnace for design analysis are:

- Heat release rate per unit cross-sectional area
- Heat release rate per unit volume
- Heat release rate per unit wall area of the burner region

16.28.1 Heat Release Rate per Unit Volume q_v

The amount of heat generated by the combustion of fuel in a unit effective volume of the furnace is given by

$$q_v = \frac{m_f \times \mathrm{LHV}}{V_{furnace}} \quad (\mathrm{kW/m^3})\,, \tag{16.73}$$

where m_f is the designed fuel consumption rate (kg/s), LHV is the lower heating value of the fuel (kJ/kg), V_f is the volume of the furnace ($a \times b \times h_f$), and h_f is the height of the furnace.

The value of q_v depends on the coal type and type of furnace.

The volumetric heat release rate also depends on the ash characteristic, firing method, and the arrangement of the burners. The proper selection of the volumetric flow

rate in accord with the heat release rate will ensure that fuel particles are substantially burned.

16.28.2 Heat Release Rate per Unit Wall Area of the Burner Region

One of the most important regions in the furnace is the burner region. The heat release rate in the burner region is calculated on the basis of the water wall in this region. The heat release rate per unit wall area of the furnace depends on the following parameters [16.16]:

1. Ash characteristic
2. Fuel ignition characteristics
3. Firing method
4. Arrangement of burners

The heat release rate per unit wall area of the burner region my be written

$$q_b = \frac{m_f \mathrm{LHV}}{2(a+b)h_b} \quad (\mathrm{kW/m^2})\,, \tag{16.74}$$

where a and b are the width and depth of the furnace, respectively, and h_b is the distance between the top edge of the uppermost burner and the lower edge of the lowest burner.

16.28.3 Heat Release Rate per Unit Cross-Sectional Area

This is the amount of heat released per unit cross section of the furnace. It is given by

$$q_f = \frac{m_f \mathrm{LHV}}{A_{\mathrm{furnace}}} \quad (\mathrm{kW/m^2})\,, \tag{16.75}$$

where A_{furnace} is the cross-sectional area of the furnace in m^2.

16.28.4 Furnace Exit Gas Temperature

The furnace exit gas temperature is an important design parameter. It determines the rate of heat absorption by the radiant heating surface in the furnace and that by the convective heating surface of the furnace. The optimum value of the furnace exit gas temperature is 1200–1400 °C.

16.28.5 Example Problem

An optimal operation test on a model steam generator gives the following information:

- Ultimate analysis: C: 63.4%, H: 5.7%, O: 16.8%, N: 10%, ash: 8.9%, moisture: 13%
- HHV of coal: 33 318 kJ/kg
- Combustible solid refuse: 7.5%
- Dry exhaust gas analysis: CO_2: 15.4%, CO: 0.5%, O_2: 2.8%, N_2: 81.3%
- Ambient conditions: 50 °C and 100 kPa
- Temperature of air entering the furnace: 235 °C

Design a PC (pulverized coal) furnace for a steam generator with a thermal capacity of 1000 MW with the following characteristics:

- Steam generator efficiency of 0.86
- Furnace quality factor of 0.406×10^8
- Temperature field coefficient of $M = 0.405$
- Thermal capacity of the gas of $c_p = 1.17\,\mathrm{kJ/(kg\,K)}$

A furnace can be characterized geometrically by its linear dimensions: front width a, the depth b, and the height h_f (Fig. 16.29), which are estimated according to the rated fuel consumption and the thermal, physical, and chemical properties of the fuel to be used.

Flow Rate of Fuel

$$\begin{aligned} Q_{\mathrm{boiler}} &= m_{\mathrm{coal}} \mathrm{HHV} \eta_{\mathrm{SG}}\,, \\ 1\,000\,000 &= m_{\mathrm{coal}} 33\,318 \eta_{\mathrm{SG}}\,, \\ m_{\mathrm{coal}} &= 34.899\,\mathrm{kg/s}\,; \\ \mathrm{LHV} &= \mathrm{HHV} - \frac{m_{\mathrm{H_2O}}}{\text{kg of fuel}} 2442\,, \\ \mathrm{LHV} &= 323\,827\,\mathrm{kJ/kg}\,. \end{aligned}$$

Here, η_{SG} is the efficiency of the steam generator.

Heat Release Rate per Unit Volume

$$q_v = \frac{m_f \mathrm{LHV}}{V_f} \quad (\mathrm{kW/m^3})\,. \tag{16.76}$$

The large content of H and O is largely volatile matter and hence the given composition is bituminous. For bituminous coal the range of value of q_v is 0.14–0.20 MW/m^3 [16.16].

Substituting the values of q_v, m_f, and LHV (Table 16.1) we find the volume of the furnace to be

$$V = 7532.05\,\mathrm{m^3}\,.$$

Heat Release Rate per Unit Cross-Sectional Area

This is the amount of heat released per unit cross section of the furnace. It is given by

$$q_a = \frac{m_f \mathrm{LHV}}{A_{\mathrm{grade}}} \quad (\mathrm{kW/m^2})\,, \tag{16.77}$$

Table 16.1 Typical values of the volumetric heat release (q_v) in MW/m^3

Coal type	Dry-bottom furnace q_v (MW/m^3)	Wet (slagging) bottom furnace q_v (MW/m^3) Open furnace	Half-open furnace	Slagging pool
Anthracite	0.110–0.140	≤ 0.145	≤ 0.169	0.523–0.598
Semi-anthracite	0.116–0.163	0.151–0.186	0.163–0.198	0.523–0.698
Bituminous	0.14–0.20	–	–	–
Oil	0.23–0.35	–	–	–
Lignite	0.09–0.15	≤ 0.186	≤ 0.198	0.523–0.640
Gas	0.35	–	–	–

Table 16.2 Upper limits of q_a for tangentially fired furnaces

Boiler capacity (t/h)	Upper limit of q_a (MW/m^2) ST[a] $\le 1300\,°C$	ST $= 1300\,°C$	ST $\ge 1300\,°C$
130	2.13	2.56	2.59
220	2.79	3.37	3.91
420	3.65	4.49	5.12
500	3.91	4.65	5.44
1000	4.42	5.12	6.16
1500	4.77	5.45	6.63

[a] ST = softening temperature of ash (°C)

where A_{grade} is the cross-sectional area of the grade in m^2

$$A_{grade} = ab = \frac{m_f \mathrm{LHV}}{q_a} \quad (\mathrm{kW/m^2})\ . \tag{16.78}$$

Substitute the value of q_a, m_f, and LHV (Table 16.2) in (16.78) we find the grade area $ab = 441.46\,m^2$.

Heat Release Rate per Unit Wall Area of the Burner Region

The heat release rate per unit wall area of the burner region may be written

$$q_b = \frac{m_f \mathrm{LHV}}{2(a+b)h_b} \quad (\mathrm{kW/m^2})\ . \tag{16.79}$$

The recommended value of the burner region heat release rate was taken as

$$h_b = 1\,\mathrm{MW/m^3}\ .$$
$$2(a+b)h_b = 1129.80\,m^2\ .$$

Based on Tables 16.1 and 16.3, corresponding to the boiler capacity, the minimum width was chosen as $b_{min} = 6\,m$ and $h_{furnace,min} = 11\,m$.

Based on the above constraints suitable values for a and b are

$$a = 20.62\,m\ ,$$
$$b = 21.4\,m\ ,$$
$$h_b = \frac{1129.8}{2(21.4+20.62)} = 13.44\,m\ .$$

The volume of the furnace region (Fig. 16.29) is therefore

$$\begin{aligned} V_{furnace} &= h_{furnace}ab \\ &\quad - \frac{a}{2}(d+d+d\tan\beta+d\tan\alpha)d\ , \end{aligned} \tag{16.80}$$

$$V_{furnace} = h_{furnace}ab - \frac{ad}{2}(2d+d\tan\beta+d\tan\alpha)\ , \tag{16.81}$$

$$V_{furnace} = h_{furnace}ab - \frac{ad^2}{2}(2+\tan\beta+\tan\alpha)\ . \tag{16.82}$$

Substituting the values of a, b, α, β, and $V_{furnace}$ into (16.82) yields

$$h_{furnace} = 19.33\,m\ .$$

To find the height of the hopper we insert the data into

$$h_h = \left(\frac{b-e}{2}\right)\tan\gamma = 14.56\,m\ . \tag{16.83}$$

From the geometry we calculate the total surface area as

$$\begin{aligned} &a(h_f+h_b)+a(h_f+h_b-d-d\tan\alpha-d\tan\beta \\ &\quad +d\sec\alpha+d\sec\beta)+2b(h_f+h_b) \\ &\quad -d(d+d+d\tan\alpha+d\tan\beta)+2\left[\frac{1}{2}h_h(b+e)\right] \\ &\quad +2ah_h\cos\mathrm{ec}\,\gamma\ . \end{aligned} \tag{16.84}$$

Table 16.3 Lower limit of h_{furnace} (m)

Boiler capacity (t/h)	65–75	130	220	420	670
Anthracite	8	11	13	17	18
Bituminous	7	9	12	14	17

Substituting all the values into (16.84), the surface area of the furnace is calculated to be 3793.98 m^2.

Adiabatic Flame Temperature

Ultimate Analysis.

$$\begin{aligned}
&\mathrm{C}: && \frac{64.4}{12}=5.283\\
&\mathrm{H}: && 5.7-\frac{13}{9}=4.255\\
&\mathrm{O}: && \frac{16.8}{16}-\left[\left(\frac{8}{9}\right)\left(\frac{13}{16}\right)\right]=0.327\\
&\mathrm{N}: && \frac{1}{14}=0.071\\
&\text{Ash} && =8.9\\
&\text{Moisture} && =\frac{13}{18}
\end{aligned}$$

$$\begin{aligned}
&\mathrm{C}_X\mathrm{H}_Y\mathrm{S}_Z\mathrm{O}_K+\left(X+\frac{Y}{4}+Z-\frac{K}{2}\right)\mathrm{O}_2\\
&\rightarrow 15.4\mathrm{CO}_2+0.5\mathrm{H}_2\mathrm{O}+2.8\mathrm{O}_2+81.3\mathrm{N}_2+Z\mathrm{H}_2\mathrm{O}
\end{aligned}$$

For 100 kg of fuel

$$\begin{aligned}
&\mathrm{C}_{5.28}\mathrm{H}_{4.25}\mathrm{O}_{0.327}+4.76\cdot 1.162\cdot 6.152\text{air}\\
&\rightarrow 5.11\mathrm{CO}_2+0.166\mathrm{H}_2\mathrm{O}+0.933\mathrm{O}_2\\
&\quad +27.1\mathrm{N}_2+2.13\mathrm{H}_2\mathrm{O}\,,
\end{aligned}$$

$$\begin{aligned}
&n_{\text{exit}}\ \text{(mole of exit gases)}\\
&=5.11+0.166+0.93+27.1+2.13=35.43\,,\\
&100\cdot 33\,318=35.43\cdot 40\cdot(T_{\text{th}}-T_{\text{atm}})\,,\\
&T_{\text{th}}=2624\,\mathrm{K}\,.
\end{aligned}$$

The ash softening temperature is $\geq 1250\,°\mathrm{C}$ and $T_{\text{out}}\leq 1250\,°\mathrm{C}=1523\,\mathrm{K}$.

100 kg of fuel generates 1056.71 of exhaust flue gas with m_{gas} for a 34.89 kg/s of flow rate of fuel, $m_{\text{gas}}=368.68\,\mathrm{kg/s}$.

To find T_{out} we use

$$A_{\text{furnace}}=\frac{Gm_{\mathrm{f}}c_{\mathrm{p}}}{T_{\text{th}}^3}\left[\frac{1}{m}\left(\frac{T_{\text{th}}}{T_{\text{out}}}-1\right)\right]^{1/0.6}\,, \qquad (16.85)$$

where G is the furnace quality factor, M is the temperature field coefficient, T_{th} is the theoretical combustion temperature, A_{furnace} is the total surface area of furnace, and m_{f} is the mass flow rate of fuel.

Substituting all these values in (16.85) we find $T_{\text{out}}=1365.95\,\mathrm{K}$.

T_{out} is $<1523\,\mathrm{K}$ (ash softening temperature), so the design is safe.

16.29 Strength Calculations

Special care must be taken in the design and stress analysis of steam generators because of the application of high pressure and temperature involved in the system. Allowable stresses in the pressure vessel depend on the nature of the loading in the pressure vessel and the response to this loading.

Stress can be classified into:

1. Primary stress
2. Secondary stress
3. Peak stress

The *primary stress* is developed by the mechanical load; it can cause mechanical failure of the vessel. An example of this kind of stress is that produced by internal pressure such as in a steam drum. *Secondary stress* is due to mechanical load or thermal expansion. *Peak stress* is concentrated in highly localized area at abrupt geometry changes.

16.29.1 Mathematical Formulae for Stress

The basic equation for the longitudinal stress σ_1 and hoop stress σ_2 in a vessel of thickness of h, longitudinal radius r_1, and circumferential stress r_2, which is subjected to a pressure p is given by

$$\frac{\sigma_1}{r_1}+\frac{\sigma_2}{r_2}=\frac{p}{h}\,. \qquad (16.86)$$

From this equation, and by equating the total pressure load with the longitudinal forces acting on a transverse section of this vessel, the stresses in the commonly used shells of revolution can be found.

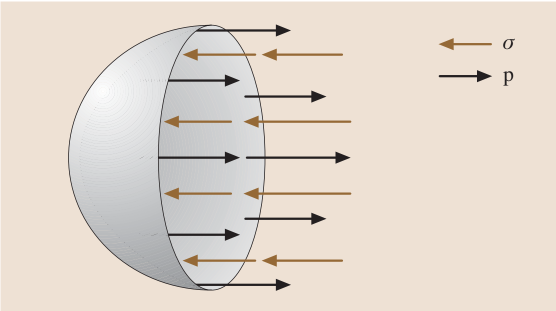

Fig. 16.49 Cross-sectional view of spherical vessel

16.29.2 Stress Analysis Methods

Stress analysis of pressure vessel can be performed by analytical or experimental methods. The general shapes of a pressure vessel are spheres, cylinders, and ellipses.

Spherical Vessel ($r_1 = r_2 = r$). Consider a spherical pressure vessel with radius r and wall thickness h subjected to an internal pressure. All four normal stresses on a small stress in the wall must be identical, due to symmetry. Furthermore there can be no shear stress. The normal stresses σ can be related to the pressure p by inspecting the free-body diagram of the pressure vessel. To simplify the analysis, cut the vessel in half as illustrated in Fig. 16.49.

The stress around the wall must have a net resultant to balance the internal pressure across the cross section

$$\sigma h 2\pi r = p\pi r^2 ,$$

$$\sigma_1 = \frac{pr}{2h} , \tag{16.87}$$

$$\sigma_2 = \frac{pr}{2h} . \tag{16.88}$$

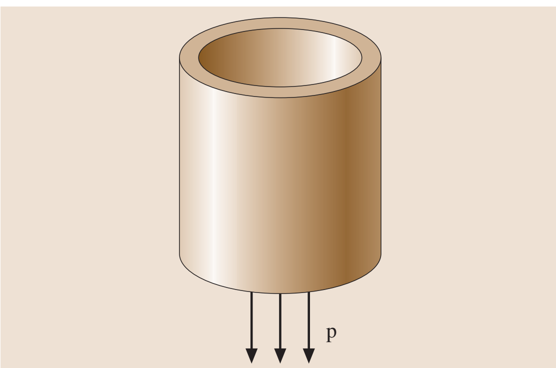

Fig. 16.50 Stress analysis of cylindrical vessel

Cylindrical Vessel ($r_1 = \infty$, $r_2 = r$).

$$\sigma_1 = \frac{pr}{2h} , \tag{16.89}$$

$$\sigma_2 = \frac{pr}{h} . \tag{16.90}$$

Conical Vessel $r_1 = \infty$, $r_2 = r/\cos\alpha$, Where α is the Half-Cone Angle.

$$\sigma_1 = \frac{pr}{2h\cos\alpha} , \tag{16.91}$$

$$\sigma_2 = \frac{pr}{h\cos\alpha} . \tag{16.92}$$

Elliptical Vessel.

$$\sigma_1 = \frac{pr_2}{2h} , \tag{16.93}$$

$$\sigma_2 = \frac{p}{h}\left(r_2 - \frac{r_2^2}{2r_1}\right) . \tag{16.94}$$

16.29.3 Design Pressure and Temperature

Generally, the design pressure is the maximum allowable working pressure. It should not be less than the highest set pressure of any safety valve. The determination of the allowable stresses is based upon the design temperature T, which should not be taken to be less than the mean wall metal temperature (through thickness) expected under operating conditions for the part considered. The design temperature is to be stated by the manufacturer on the drawings of the pressure parts submitted for consideration.

The design of pressure parts is based on the allowable stress S in $\mathrm{N/mm^2}$.

The minimum thickness of straight tubes is to be determined as

$$t = \frac{pD_o}{20SE + p} + C , \tag{16.95}$$

where p is the design pressure (bar), t is the minimum thickness (mm), D_o is the outside diameter (mm), S is the allowable stress ($\mathrm{N/mm^2}$), E is the weld efficiency of longitudinally welded tubes, and C is the corrosion allowance (mm).

The efficiency factor E is the welding efficiency of the longitudinal joint or of ligaments between tube holes or other openings.

16.30 Heat Transfer Calculation

16.30.1 Heat Exchangers

Heat exchangers play a vital role in power plant to transfer heat from hot to cold fluids. Heat exchangers with different flow configurations such as parallel flow, counterflow, and crossflow types are generally used.

Heat Transfer Analysis in a Counterflow Heat Exchanger

A counterflow heat exchanger, where the fluid moves in parallel but opposite direction, is shown in Fig. 16.51.

The thermal design of a heat changer involves the calculation of the surface area required to transfer heat at a given rate for given flow rates and fluid temperatures. The size of the heat exchanger can be obtained from the general heat transfer equation,

$$Q = U_o A_o \Delta T_{lm} , \tag{16.96}$$

where A_o is the outside heat transfer surface area based on the outside diameter of the tube, U_o is the overall heat transfer coefficient based on the outside diameter of the tube, and ΔT_{lm} is the log mean temperature difference

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} , \tag{16.97}$$

where $\Delta T_1 = T_{h1} - T_{c2}$ and $\Delta T_2 = T_{h2} - T_{c1}$ for a counterflow heat exchanger.

16.30.2 Flow Resistance

Friction resistance values for the actual pipes and volume flows may be obtained from special charts made for the pipes or tubes considered.

Minor pressure losses due to fittings as bends, elbows, valves, and similar may be calculated as

$$p_2 = \xi \frac{\rho v^2}{2} \quad \text{or expressed as } \textit{head} \tag{16.98}$$

$$h_{loss} = \xi \frac{v^2}{2} g , \tag{16.99}$$

where ξ is the minor loss coefficient, p_{loss} is the pressure loss (Pa = N/m^2), ρ is the density (kg/m^3), v is the flow velocity (m/s), h_{loss} is the head loss (m), and g is the acceleration of gravity (m/s^2).

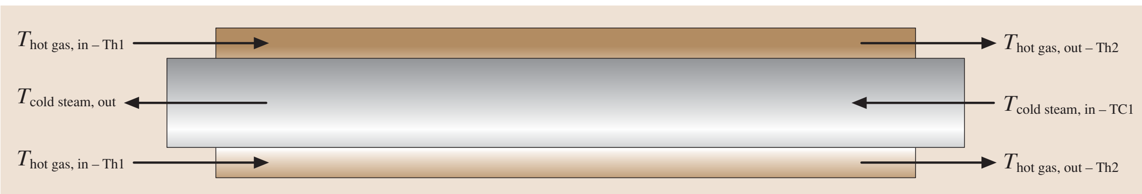

Fig. 16.51 Heat transfer along a heat exchanger

16.31 Nuclear Reactors

Nuclear reactors are devices designed to maintain a chain reaction producing neutrons generated by the fission of heavy nuclei. Nuclear power plants utilizing power reactors are dedicated to generate heat, mainly for electricity production. They are operated in more than 50 countries [16.17].

16.31.1 Components of a Nuclear Reactor

The major components of a nuclear reactor are:

1. The fuel core
2. The moderator and coolant
3. The control rods
4. The reactor vessel

Fuel Core

The fuel core contains the nuclear fuel and is the part of the reactor where the fission reaction takes place. The nuclear fuel may be either natural or enriched uranium. Natural uranium contains 0.71% fissile ^{235}U and 99.28% fertile ^{238}U and fertile thorium Th-232. The enriched uranium is produced in a gaseous diffusion process and is expected to have a ^{235}U content of 2–33%.

The nuclear fuel is generally contained in cylindrical rods surrounded by cladding materials. The fuel-rod

cladding materials must not only be able to maintain the shape of the fuel rod, but also to sustain the reactor conditions. Materials used for these components include aluminum, magnesium, stainless steel, and graphite.

Moderator and Coolant

The moderator is the substance used in a nuclear reactor to reduce the energy of fast neutrons to thermal neutrons. Liquid and solid materials with low atomic mass number and low neutron capture cross section should be suitable. These include light water, heavy water, carbon, and beryllium.

The reactor coolant is used to remove heat from the reactor fuel core. The conditions for a better coolant include high specific heat, high thermal conductivity, and high boiling point at low pressure. The coolant should also have low power demand for pumping, low cost, and a high degree of stability in the reactor environment.

Control Rods

Control rods are used to slow down or speed up a chain reaction. Elements like boron and cadmium are used in a control rod to absorb fast neutrons and thereby control the chain reaction. An automatic retractable mechanism helps to insert the control rods into the fuel core or withdraw them to slow down or speed up the chain reaction. Shim rods, regulating rods, and safety rods are three different types of control rods.

Reactor Vessel

The reactor vessel is a tank-like structure that holds the reactor core and other internal components. The walls of the vessel are designed for a high-pressure radiation environment. In most cases the vessel walls are lined with thick steel slabs to reduce the flow of radiation from the core. As indicated in the last section, nuclear fission generates large amounts of neutrons and gamma rays, both of which are very harmful. Because of these, biological shielding is required around the reactor vessel. This shield consists of concrete blocks, which may be up to 2 m thick.

16.31.2 Types of Reactors

There are four types of reactors:

1. Pressurized water reactors (PWR)
2. Boiling water reactors (BWR)
3. Pressurized heavy-water reactor (PHWR)
4. Gas-cooled reactors (Magnox)

When ^{235}U is bombarded with neutrons, fission reactions take place, releasing neutrons that fission more atoms of ^{235}U. In order that the freshly released neutrons are able to fission further uranium atoms, their speeds must be reduced to a critical value. Therefore, for the reaction to be sustained, nuclear fuel rods must be embedded in neutron speed-reducing agents (such as graphite and heavy water) called moderators. For reaction control, rods made of neutron-absorbing material (boron steel) are used which, when inserted into the reactor vessel, control the amount of neutron flux, thereby controlling the range. A schematic diagram of a nuclear power plant is shown in Fig. 16.52. The heat released by the nuclear reaction is transported to a heat exchanger via primary coolant (CO_2, water etc.). Steam is then generated in the heat exchanger, which is used in a conventional manner to generate electric energy by means of a steam turbine. Various types of reactors are used in practice for power plant purposes, viz. advanced gas reactors (AGR), boiling water reactors (BWR), heavy-water-moderated reactors, etc.

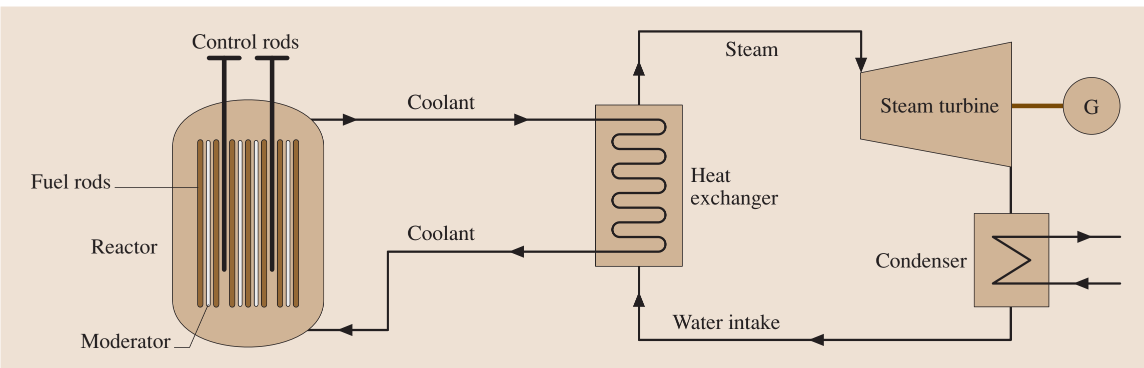

Fig. 16.52 Schematic view of a nuclear power plant

The CANDU reactor using natural uranium (in oxide from), moderated using pressurized heavy water is adopted in India. Its schematic diagram is shown in Fig. 16.53.

The associated merits and problems of nuclear power plants as compared to conventional thermal plants are discussed in the next paragraphs.

Merits and Demerits of Nuclear Power Plants

Merits. A nuclear power plant is totally free of air pollution and requires little fuel in terms of volume and weight; it therefore poses no transportation problems and may be sited, independently of nuclear fuel supplies, close to load centers. However, safety considerations require that they are normally located far away from populated areas.

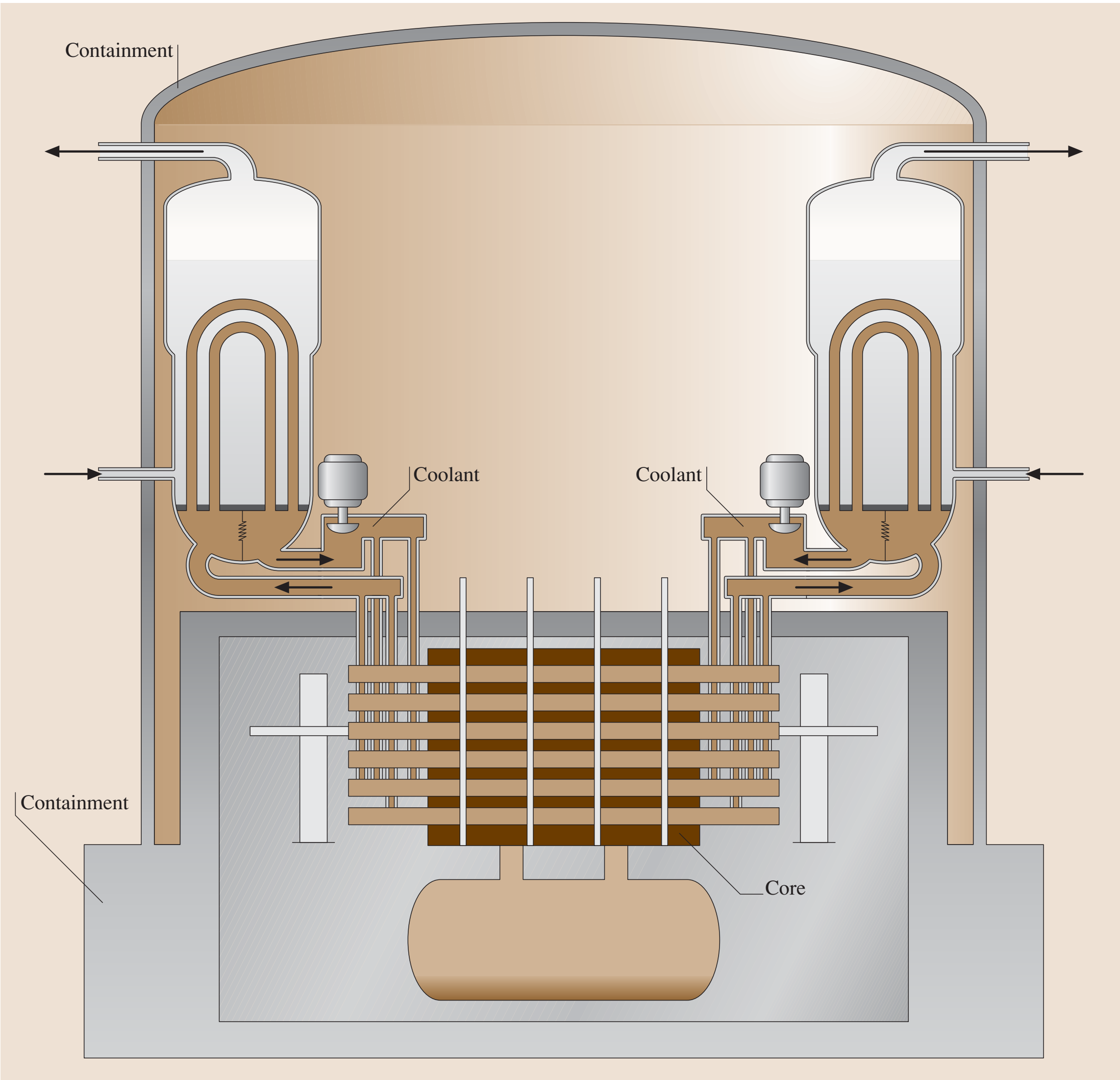

Fig. 16.53 CANDU reactor. Pressurized heavy-water-moderated design adopted in India

Demerits. Nuclear reactors produce radioactive fuel waste, the disposal of which poses serious environmental hazards. The rate of nuclear reaction can be lowered only by a small margin, so that the load on a nuclear power plant can only be marginally reduced below its full load value. Because of the relatively high capital cost against running cost, the nuclear plant should operate continuously as the base load station. Whenever possible, it is preferable to support such a station with a pumped storage scheme mentioned earlier. The greatest danger in a fission reactor is in the case of the loss of coolant in a accident. Even with the control rods fully lowered quickly, called a scram operation, fission continues and its afterheat may cause the vaporization and dispersal of radioactive material.

World uranium resources are quite limited, and at the present rate may not last much beyond 50 years. However, there is a redeeming feature. During the fission of ^{235}U some of the neutrons are absorbed by the more abundant uranium isotope ^{238}U (enriched uranium contains only about 3% of ^{235}U while most of it is ^{238}U) converting it to plutonium (^{239}U), which in itself

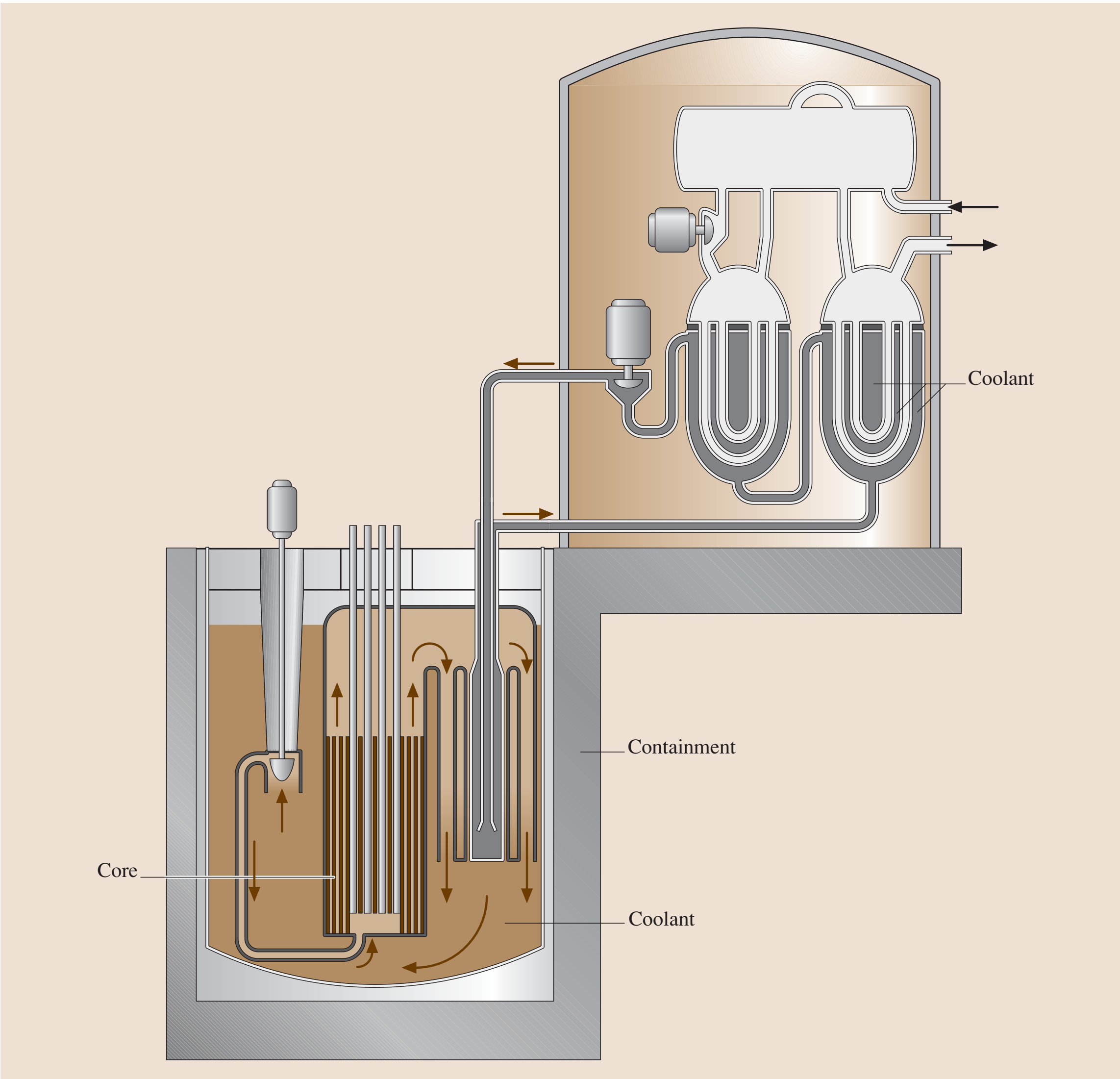

Fig. 16.54 A fast breeder reactor

is a fissionable material and can be extracted from the reactor fuel waste by a fuel reprocessing plant. Plutonium can then be used in the next-generation reactors (fast breeder reactors (FBRs)), thereby considerably extending the life of nuclear fuels. The FBR technology is being intensely developed as it will extend the availability of nuclear fuels at predicted rates of energy consumption to several centuries.

Figure 16.54 shows the schematic diagram of an FBR. It is essential that, for breeding operation, the conversion ratio (fissile material generated/fissile material consumed) is more than unity. This is achieved by fast-moving neutrons so that no moderator is needed, although the neutrons do slow down slightly through collision with structural and fuel elements. The energy density/kg of fuel is very high and so the core is small. It is therefore necessary that the coolant should possess good thermal properties; hence liquid sodium is used. The fuel for an FBR consists of 20% plutonium plus 8% uranium oxide. The coolant, liquid sodium, leaves the reactor at 650 °C at atmospheric pressure. The heat transported in this way is led to a secondary sodium circuit which transfers it to a heat exchanger to generate steam at 540 °C.

With a breeder reactor the release of plutonium, an extremely toxic material, make the environmental considerations very stringent.

An experimental fast breeder test reactor (FBTR) (40 MW) has been built at Kalpakkam alongside a nuclear power plant. FBR technology is expected to reduce the cost of electric energy so that it compares favorably with that from conventional thermal plants.

16.32 Future Prospects and Conclusion

Various advanced power generation technologies have been described in this chapter. Many regions of the world are experiencing fast growing electricity demand. Advanced technologies such as IGCC, ultra-supercritical cycles, and advanced gasification molten carbonate fuel cell cycles allow this electricity demand to be met and emission levels from power plants to meet air quality standards. Fluidized-bed combustion is an environmentally benign and proven technology for the disposal of solid wastes and the generation of electrical energy. Technological advancement will improve the reliability and efficiency of energy conversion process. The integrated gasification combined cycle will be able to exploit various kinds of low-grade energy resources such as biomass, low-grade coal, oil residues etc., for the sake of efficient power production. The development of advanced materials to withstand high temperatures as well as high pressures will enhance the thermal efficiency to 55%. Even a fraction of a percentage improvement in efficiency can mean huge savings in annual fuel cost.

Cogeneration of heat as well as electric power is one of the attractive options from the cost–benefit point of view; it saves 30–40% of fuel input energy. A combined cycle employing cogeneration using a multicomponent fluid such as an ammonia–water mixture will improve the thermal efficiency further. Effective utilization of renewable sources of energy including hydropower, solar, wind, and biomass is one of current the challenging tasks for researchers. The potential of solar power is unlimited; it is our prime task to utilize this energy in a more effective way. The development of solar technology seeks to achieve efficient operation even though solar energy intensity varies according to weather and time of day.

With the end of coal reserves in sight in the not too distant future, the immediate practical alternative source of large-scale electric energy generation is nuclear energy. The latest power plant technologies and dedicated research will lead to efficiencies approaching the Carnot efficiency in the near future.

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